Naval Research Laboratory
Washington, DC 20375-5320

NRL/6170/MR--20234

Technology Assessment of Water Treatment Devices for Small-Scale Production

Paul A. DeSario
Jeffrey W. Long
Kenan P. Fears

Surface Chemistry Branch
Chemistry Division

October 17, 2023

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
17-10-2023

2. REPORT TYPE
NRL Memorandum Report

3. DATES COVERED *(From - To)*
7/7/22 – 9/18/23

4. TITLE AND SUBTITLE

Technology Assessment of Water Treatment Devices for Small-Scale Production

5a. CONTRACT NUMBER
N0001422WX00047

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
2A43

6. AUTHOR(S)

Paul A. DeSario, Jeffrey W. Long, and Kenan P. Fears

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Research Laboratory
4555 Overlook Avenue, SW
Washington, DC 20375-5320

8. PERFORMING ORGANIZATION REPORT NUMBER

NRL/6170/MR--2023/4

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research
875 N. Randolph Street,
Code 08
Arlington, VA 22217-1995

10. SPONSOR / MONITOR'S ACRONYM(S)

O(NR

11. SPONSOR / MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

Report was routed through ONR security and cleared for public release (DCN: 0543-1045-23).

14. ABSTRACT

Potable water supply is a long-standing challenge for military missions and critical to maintaining warfighter performance. The U.S. Armed Forces currently rely on large, centralized reverse-osmosis (RO) water-treatment systems for production of potable water, which must then be distributed to its point-of-use. Delivering water to remote expeditionary operations is logistically demanding, dangerous, and expensive. The Navy and DoD have recently developed RO desalination systems that adequately scale to the platoon level (45 warfighters), but further down-scaling to squad level (13 warfighters) or below is a challenge for RO. Other drawbacks of RO include maintenance and lifetime issues associated with the membranes and a high consumables burden. Because of increasing global concerns about civilian drinking water supplies, many alternative desalination/purification technologies are under development, including various electrochemical methods (e.g., "capacitive deionization") that are electrically driven, thermal processes that use solar input, and atmospheric-water harvesting techniques that bypass the need for direct desalination. Herein, we summarize performance requirements for small-scale (squad-level to individual) water-treatment systems, recount recent development and demonstration of RO technologies for Navy and DoD uses, and highlight more nascent investments in alternative (non-RO) approaches at the time of this report. We provide an assessment of emerging desalination/water-generation techniques, noting particularly their advantages and disadvantages in terms of scalability, energy efficiency, and throughput. Electrochemical approaches that borrow materials and mechanisms from aqueous battery chemistry are projected to be the most relevant for direct desalination needs with such requirements, while atmospheric-water generation should also have utility to meet potable water needs in certain environments and missions.

15. SUBJECT TERMS

Desalination	Potable water	Water purification	Reverse osmosis
Capacitive deionization	Atmospheric water	Logistics	Expeditionary missions

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Paul A. DeSario
U	U	U	U	64	**19b. TELEPHONE NUMBER** *(include area code)* (202) 404-0417

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

This page intentionally left blank.

CONTENTS

NOMENCLATURE

1 gallon = 3.785 L

AEM: Anion-exchange Membrane

AWE: Atmospheric Water Extraction

AWG: Atmospheric Water Generation

AWH: Atmospheric Water Harvesting

Battalion: a larger military unit comprising several companies

Brackish water: 1 g/L to 5 g/L total dissolved salts

CDI: Capacitive Deionization

CEM: Cation-exchange Membrane

Company: 130 individuals

CoI: Community of Interest

CoP: Community of Practice

COTS: Commercial-off-the-shelf

DEDI: Dual-ion Intercalation Electrochemical Desalination

EABO: Expeditionary Advanced Base Operations

ED: Electrodialysis

Fresh water: <1 g/L total dissolved salts

FO: Forward Osmosis

FOB: Forward Expeditionary Base

GPD: gallons per day

GREENS: Ground Renewable Expeditionary Energy Network System

HCDI: Hybrid Capacitive Deionization

ICP: Ion Concentration Polarization

IDI: Intercalative Deionization

IEM: Ion-exchange Membrane

IPT: Integrated Product Team

KPP: Key Performance Parameter

KSA: Key System Attribute

kWh: kilowatt-hour (unit of energy)

LNPWPS: Low Power/No Power Water Purification System

LPD: liter per day

LWPS: Lightweight Water Purification System

mCDI: Membrane Capacitive Deionization

MCSC: Marine Corps Systems Command

MD: Membrane Distillation

Osmotic Pressure: Pressure required to stop the net movement of water across a permeable membrane

Platoon: 45 individuals

PCM: Phase-change material

psi: pounds-per-square-inch

PVT: Production Verification Testing

PWPS: Platoon Water Purification System

RCDI: Rocking-chair Capacitive Deionization

RH: Relative Humidity

RO: Reverse Osmosis

ROWPU: Reverse Osmosis Water-Purification Units

SBIR: Small Business Innovative Research

SDEI: Solar-driven Interfacial Evaporation

Seawater: >15 g/L to 45 g/L (35 g/L typical) total dissolved solids

SGE: Salinity-gradient Energy

SoO: Statement of Objectives

SPACES: Solar Portable Alternative Communication Energy System

Squad: 13 individuals

SWaP: Size, Weight, and Power

SWPS: Squad Unit Water Purification System

TDS: Total Dissolved Solids**;** a measure, in mg/L, g/L, or parts-per-million, of the dissolved constituents in an aqueous solution, including salts and minerals

TEC: Thermoelectric Cooling

TICS: Toxic Industrial Chemicals

TIMS: Toxic Industrial Materials

TSS: Total Suspended Solids

TRL: Technology Readiness Level

TWPS: Tactical Water Purification System

VCR: Vacuum Compression Refrigeration

Wh: Watt-hour (unit of energy)

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

Financial support for the assembly of this report was provided by the Office of Naval Research (ONR). The authors particularly acknowledge ONR Program Manager, Joseph F. Parker for proposing and supporting this study.

This page intentionally left blank.

EXECUTIVE SUMMARY

Potable water supply is a long-standing challenge for military missions and critical to maintaining warfighter performance. The U.S. Armed Forces currently rely on large, centralized reverse-osmosis (RO) water-treatment systems for production of potable water, which must then be distributed to its point-of-use. Delivering water to remote expeditionary operations is logistically demanding, dangerous, and expensive. The Navy and DoD have recently developed RO desalination systems that adequately scale to the platoon level (45 warfighters), but further down-scaling to squad level (13 warfighters) or below is a challenge for RO. Other drawbacks of RO include maintenance and lifetime issues associated with the membranes and a high consumables burden. Because of increasing global concerns about civilian drinking water supplies, many alternative desalination/purification technologies are under development, including various electrochemical methods (*e.g.*, "capacitive deionization") that are electrically driven, thermal processes that use solar input, and atmospheric-water harvesting techniques that bypass the need for direct desalination. Herein, we summarize performance requirements for small-scale (squad-level to individual) water-treatment systems, recount recent development and demonstration of RO technologies for Navy and DoD uses, and highlight more nascent investments in alternative (non-RO) approaches at the time of this report. We provide an assessment of emerging desalination/water-generation techniques, noting particularly their advantages and disadvantages in terms of scalability, energy efficiency, and throughput. Electrochemical approaches that borrow materials and mechanisms from aqueous battery chemistry are projected to be the most relevant for direct desalination needs with such requirements, while atmospheric-water generation should also have utility to meet potable water needs in certain environments and missions.

This page intentionally left blank.

1. INTRODUCTION

Potable water is an essential supply for any military mission that involves personnel.[1,2,3] Beyond the essential task of sustaining personal hydration, potable water is also required for food preparation, basic personal hygiene, and medical treatment, among other uses. Personal consumption rates vary based on such factors as mission duration and environmental conditions. Typical "sustaining" levels of potable water are on the order of 8–10 gallons/per day/per person (gpd/person) for conventional theater operations and are as low as 3 gpd/person for short-duration missions at "minimal" sustainment levels.[1,3,4] Even potable-water delivery (or on-site generation) for minimal sustainment poses a significant logistical challenge. Potable water must also meet minimum purity specifications (*i.e.*, TB Med 577 standards[5]) in terms of factors that include "total dissolved solids" (TDS), other ionic constituents (*e.g.*, chloride), toxic metals (*e.g.*, arsenic), toxic organics (environmental pollutants or chemical warfare agents), and biological threats (*e.g.*, pathogens). These specifications are necessary to ensure the health, readiness, and effectiveness of the warfighter.

Figure 1. A U.S. Marine consumes water from canteen during exercises at Camp Pendleton, CA (U.S. Marine Corps photo by Pfc. Frank Cordoba).

Manuscript approved October 11, 2023.

High-quality drinking water is generated at large scales at centralized facilities using well-established technology and reliable feed sources. The resulting potable water eventually reaches its point-of-use through a complicated storage and distribution infrastructure.[3,4,6] Yet, distributing water (often as individually sized water bottles)[6] to active theaters is often dangerous, expensive, energy-intensive, and ultimately unsustainable, as recently noted by authors from the U.S. Army War College.[7] The Marine Corps' "Expeditionary Advanced Base Operations" strategy[8] for anticipated operations in the Pacific Theater and beyond is a prime example illustrating this logistics conundrum. The success of the EABO strategy relies principally on the deployment and sustainment of highly mobile, low-signature, small-unit operations to project forward forces in highly coordinated, but dispersed, expeditionary missions. This transition in deployment strategy is forcing planners to rethink their logistics for supporting such operations with essential supplies, including potable water.[9] The DoD is now investing in new decentralized water generation/purification technologies and associated support strategies to address potable-water logistics challenges for near-future operations.

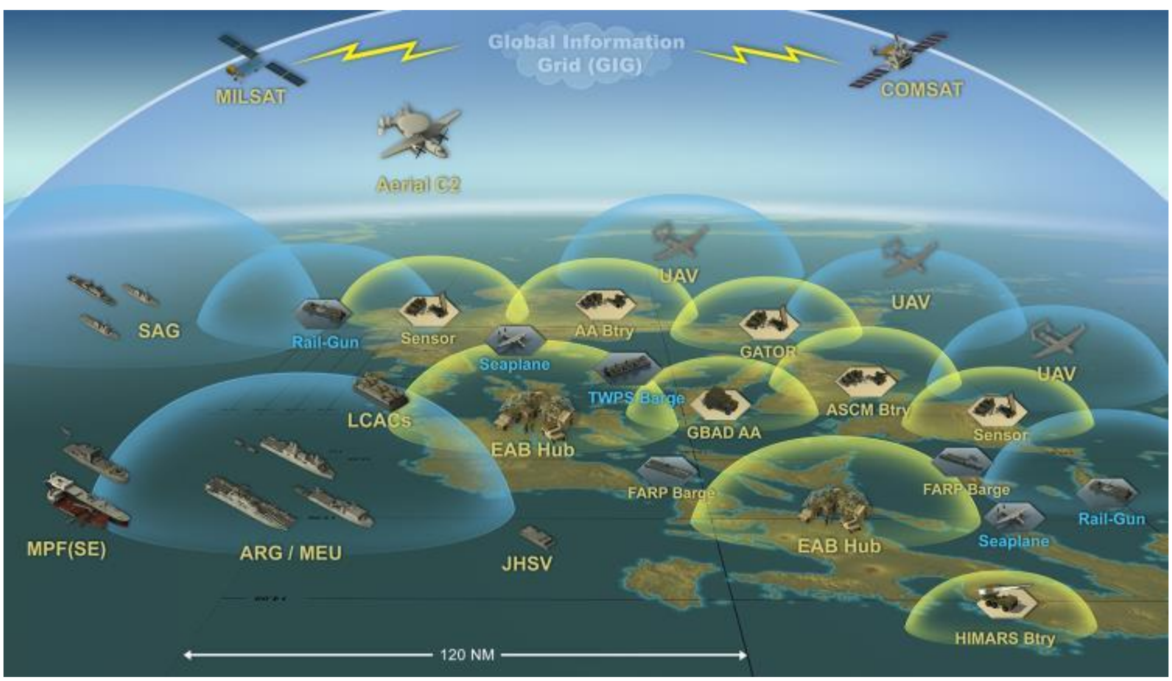


Figure 2. Official Marine Corps graphic illustrating the EABO concept.

Because there is no guarantee that the warfighter will have access to a regional freshwater source, technologies that have the ability to treat abundant seawater or brackish inland water are advantageous. Beyond the ability to purify fresh or seawater to DoD potability standards under a broad range of physical conditions (*e.g.*, temperature variations), such technologies must also meet multiple other requirements: (*i*) fast throughput of water to maintain mobility and agility; (*ii*) minimal detectable signature to maintain stealth; (*iii*) energy efficiency to reduce the need to carry additional batteries or fuel; (*iv*) low maintenance and minimal tending time to free operators for other tasks; and (*v*) reduced dependence on expendable supplies such as chemical additives to simplify logistics. Ultimately, such water systems may also need to be selected or tailored for specific missions or operating environments.

The U.S. Navy, Marine Corps, and Army have developed and deployed early generations of small-scale desalination technologies.[4] At large scales, reverse osmosis (RO)—a pressure-driven process—is unrivaled in its ability to reliably purify fresh, brackish, or seawater to meet bulk potable-water demand, and thus is used for shipboard water purification and to supply DoD ground systems. Although RO units have been scaled down to meet potable water demands at the platoon, company, or battalion levels,[4,6] this technology is difficult to scale further. Therefore, the need for small-scale desalination devices has spurred recent DoD investments in alternative desalination technologies.

Meanwhile in civilian sectors, potable-water production has been identified as a major global challenge for the 21st century due to increasing population and living standards, and the relatively scarcity of naturally occurring fresh water. The area of water desalination/purification technology has experienced continued investment from the basic science/engineering level to the testing and implementation of new potable-water generation systems at a variety of scales and geographic locales.[10,11] Well-established pressure-driven, membrane-based approaches such as RO continue to be optimized and implemented, while several alternative technologies are also emerging. For example, capacitive deionization (CDI) utilizes direct electrical input (voltage or current) to electrostatically attract ions from salt solutions at oppositely charged high-surface area electrodes, reducing salinity at the output. Newer variants of such electrochemical systems use electrode materials borrowed from battery chemistries to enhance ion-storage capacity in desalination mode. Solar-powered desalination technologies (*e.g.*, solar distillation, solar-thermal evaporation) may also be attractive in regions of the world with abundant sunlight. Atmospheric-water-harvesting (AWH) approaches bypass the challenges associated with desalination by extracting local atmospheric water in areas with reasonable levels of humidity.

All of these water generation/purification approaches require substantial energy input. As a general example, the water sector in the U.S. accounts for up to 4% of total energy consumption.[10] The recognition of the intimate association of water and energy challenges has been dubbed the "Water–Energy Nexus," reminding scientists, engineers, and planners that energy efficiency must always be considered for the implementation of water technologies. Certain water-purification schemes, including RO and electrochemical deionization, can be designed to partially recover energy initially expended in the desalination cycle, ultimately decreasing overall energy consumption per unit water produced. Techniques such as solar-thermal evaporation take advantage of renewable and locally sourced energy to drive the desalination process, reducing the reliance on external power. Energy efficiency is an even greater consideration for mobile military missions, where individual warfighters and small units must already carry a considerable weight/volume of batteries or other sources to power critical hardware before even considering the needs of any power-consuming water-purification systems.

Given the convergence of potable-water technology interest and development in the civilian sector, and the emerging need for energy-efficient, portable water purification for present and anticipated military missions, the timing is right to re-examine Navy and DoD strategies for potable-water logistics. In the following report, we first summarize recent Navy/DoD investments in mobile desalination technology (primarily based on RO methods). Drawing from the burgeoning scientific literature on water desalination/purification over the past decade, we then discuss emerging technologies that include electrical/electrochemical desalination (and several variants thereof), direct and indirect solar-powered approaches, and atmospheric-water collection schemes. For each technology, we describe their basic design and separation mechanisms, and highlight known performance attributes. Finally, we provide recommendations for near-future basic research investments in DoD-relevant emerging approaches for potable-water generation, associated testing/validation, as well as supporting technologies (*e.g.*, fieldable water-quality sensors/tests).

2. BACKGROUND

The U.S. DoD has a long history developing, validating, and fielding new technologies for potable-water generation, with individual services sponsoring their own activities. For the Navy and Marine Corps, water-purification testing and support is provided by the Seawater Desalination Test Facility (SDTF) located at the Naval Facilities Engineering Command (NAVFAC), Engineering and Expeditionary Warfare Center (EXWC) in Port Hueneme, CA. The SDTF has an operating permit from the State of California that allows up to 1 MGD of natural seawater to be pumped and discharged back to the ocean. It is a unique test facility within DOD and private sector where various water purification systems and components can be tested on natural seawater.

The Army splits these responsibilities between the Ground Vehicles System Command in Warren, MI and the Natick Soldier Systems Center in Natick, MA, with the former being responsible for large-scale systems and the latter for individual hydration needs. Other sponsor agencies such as the Office of Naval Research (ONR), Army Research Office (ARO), and Defense Advanced Research Projects Agency (DARPA) have also been involved in supporting such efforts. The following sections highlight recent developments in potable-water technologies as overseen by these DoD offices.

2.1. PRESENT WATER-SUPPLY INFRASTRUCTURE

Reverse Osmosis Water Purification Units (ROWPUs) have been the standard for supplying DoD ground systems with potable water since the first unit was fielded in 1981.[6,12] These mobile units produce potable water that meets TB Med 577 standards[5] from any available source, including freshwater or seawater. Currently, no other treatment technology has the versatility to purify seawater or freshwater with an efficiency and reliability commensurate with these RO units.[13] A summary of the key system attributes of ROWPUs that are fielded or in development is provided in **Table 1**, and an example ROWPU in operation is shown in **Figure 3**.

Table 1. Summary of Reverse Osmosis Water-Purification Units fielded by the USMC or in development. Compiled from references 3, 4, 6, 12, 13, and 19.

System	Scale and production rate	Input	Status?
600 ROWPU	• 450 gph (sea), 600 gph (fresh)	Fresh/seawater	Fielded 1981 replaced by TWPS in 2004
3000 ROWPU	• 2,000 gph (sea), 3,000 gph (fresh) • Bulk production, storage, and distribution for Battalion	Fresh/seawater	Fielded 1989, phased out for TWPS/LWPS
Tactical Water Purification System (TWPS)	• 1,200 gph (sea); 1,500 gph (fresh) • Bulk production, storage, and distribution for Battalion	Fresh/seawater	2004–present 2030 target for replacement
Lightweight Water Purification System (LWPS)	• 75 gph (sea); 125 gph (fresh) • Bulk production, storage, and distribution for Company (130 individuals)	Fresh/seawater	2005–present
Platoon Water Purification System (PWPS)	• 18 gph (sea); 22 gph (fresh) • Basic hydration needs for Platoon (45 individuals): 3.3 gal/Marine/day	Fresh/seawater	2021–present
Squad Unit Water Purification system (SWPS) or Low Power No Power Water Purification system (LNPWPS)	• 6 gph (brackish); 10 gph (fresh) • basic hydration needs of Squad (13 individuals): 3.3 gal/Marine/day	Fresh/brackish	• 2019: Statement of Objectives • In development

Figure 3. A Reverse Osmosis Water Purification Unit, ROWPU, processing lake water to potable water (filling bladders in the foreground) at Joint Base Lewis-McChord, Washington (US Army photo by Spc. Thomas X. Crough/Released).

Since the first ROWPUs were fielded, the units have been scaled down and the efficiency of RO technologies has been improved through a combination of advanced membrane designs, better prefiltration, and the utilization of more efficient pumps and energy-recovery devices. For example, the Tactical Water Purification System (TWPS), which was fielded in 2005, produces ~2× the potable-water output as legacy 600 ROWPUs in roughly the same footprint and weight.[4,6,12,13] Yet, the ROWPUs have a much higher energy demand for potable water generation[6,12,13] compared to large-scale reverse osmosis plants (**Figure 4**). [14,15]

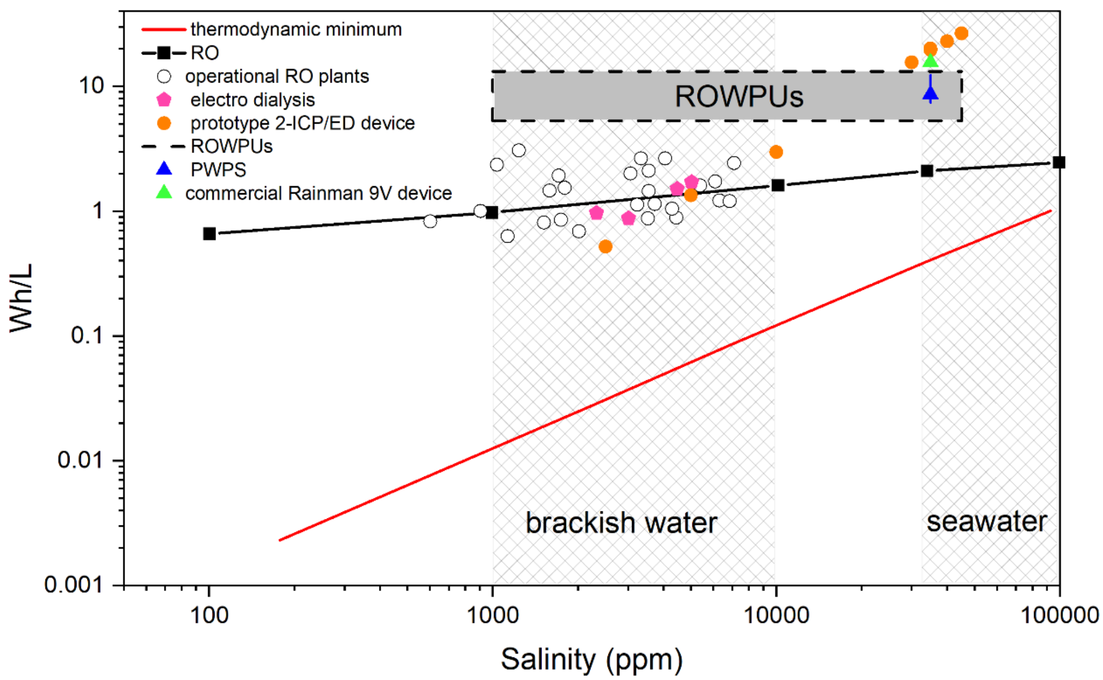


Figure 4. Energy efficiency versus salt concentration for water desalination technologies. Relative to the thermodynamic minimum (solid red line), practical reverse osmosis requires additional energy input (black line). Large-scale RO plants operate near the practical limit (open circles), but smaller-scale ROWPUs (shaded gray area) and small-scale commercial RO units are less efficient (green triangle). Estimated performance range of PWPS are overlaid (blue triangle) with brackets showing the target operational range (references 4, 20, 21). Also overlaid are test results from prototype ion concentration polarization device (reference 26). Figure adapted from Metzger *et al. Energy Environ. Sci*. 13 (2020) 1544–1560. Copyright 2020, Royal Society of Chemistry. DOI: 10.1039/D0EE00725K.

Although ROWPUs have been the lifeblood of the ground forces for decades, these systems have many well-documented deficiencies, as do all RO technologies. The units have a high consumables burden, and require replacement membranes and the addition of anti-scalants, anti-foulants, and disinfectants.[3,4] The RO process inherently requires high pumping costs and therefore is energy intensive. The RO units necessitate highly trained individuals for their operation and maintenance, and even the most skilled operator will find it difficult to diagnose malfunctions and make repairs.[4] Regular shutdowns for filter back-flushing and membrane maintenance disrupts water supply.[4] Despite these limitations, large-scale DoD ground forces will continue to rely upon some form of ROWPUs until a more reliable and versatile treatment technology is developed.

The presently fielded ROWPUs range in size to provide enough bulk water production, storage, and distribution to support the battalion level (LWPS; see **Figure 5**) down to the platoon level (18–22 gph, 45 individuals).[4,6,12] Despite reductions in size, even the smallest fielded ROWPU is not ideally suited for small-unit operations and small-unit operations presently rely on bulk-liquid distribution either by air-dropping bottled water or trucking purified water from a Forward Operating Base (FOB).[6] Establishing a means of decentralized potable water production from local resources in an austere environment is the only way to mitigate the risk of supply disruptions for small-unit operations.

Figure 5. A Lightweight Water Purification System (LWPS) operating at Fort Pickett, VA (U.S. Marine Corps photo by Sgt. Kyle N. Runnels).

2.2. Operational and Design Targets for Small-Unit and Individual Water-Treatment Devices

Given the lack of commercial technologies that are scalable for small-unit operations, DoD agencies have recently made targeted research investments to overcome the deficiencies in small-scale desalination devices. Although individual water-treatment devices have been a priority for decades, and DoD investments in small-scale/individual water-treatment devices predate the adoption of expeditionary priorities, it is only more recently that system performance metrics, operational requirements, and design criteria have been specifically refined to meet the typical mission profiles of the future force. Whereas previous capability documents did not explicitly specify the need for desalination, a more recent 2018 U.S. Army Small Business Innovation Research (SBIR) topic included a specification for seawater treatment.[16]

Recent performance objectives specified for individual,[16,17,18] squad scale,[19] and platoon scale devices,[19] outlined in calls for proposals are summarized in **Table 2**. Although exact system requirements vary depending upon the scale of the treatment system, there is one consistency that highlights a clear strategic shift: ***we can no longer take for granted that the warfighter will have access to local freshwater sources***. As a result, the ability to desalinate saltwater or to extract water from humid air has become an explicit objective for recent research efforts sponsored by the USMC, the U.S. Army, and DARPA for small unit water supply. Unlike the larger ROWPUs, which are tasked with bulk water production for storage and distribution, the small-unit/individual treatment devices are only required to meet the basic hydration needs of the warfighter (~3.3 gallons per individual per day) for a specified period of time.[4,6,16,17,18,19]

Recent efforts by the USMC have focused on the development of squad- and platoon-scale devices, while U.S. Army and DARPA have focused on individual-scale devices **(Table 2)**. In 2015, Marine Corps Systems Command (MCSC) issued an SBIR topic (N153-127) that outlined general size, weight, and system output specifications for a platoon water purification system (PWPS; see **Figure 6**) and a Squad Unit Water Purification System (SWPS, also called the Low Power/No Power Water Purification system or LNPWPS).[19]

Table 2. Summary of previously established water treatment requirements for small-scale treatment devices at platoon, squad, individual level, or equivalent thereof.

Agency/Document	Operational Requirements	Size and Weight Requirements	Design Criteria	Power Requirements
USMC Low Power Water Purification System SBIR N153-127 2015	Squad: 6–10 gph (salt or brackish not specified) Platoon: 12–30 gph (90 gpd) from saltwater	Squad: <1.5 ft^3, <10 lbs Platoon: <15.5 ft^3, <84 lbs,	• auto test capability • single operator • Operate in any MIL-STD0810G climate	• "energy efficient," • minimal battery, fuel, or operator mechanical energy • <100 W
US Army SBIR 2018 Individual A18-149	1 L/h/soldier, <9 people from sea or brackish (0.26 gph per person) 135 L/person before maintenance	<16 oz./person	• water temp. 4–49 °C; environment temp –33 to 52 °C • <20 min treat to drink time, <15 min hands-on time	• no or minimal external power; human powered preferred • commercial battery counts toward weight
DARPA, man-portable, low-power individual water purification system 2015, SB151-002	1.7 L/h (0.45 gph), 40 L/d (10.6 gpd)	<4kg (8.8 lbs) -include storage system	Operate for 20 days or purify 800 L (211 gal) before maintenance	"minimal" battery power
DARPA AWE, BAA HR001120S0014 2019	5.5–7.5 L/d (1.5–2 gpd)	<2.5 kg (5.5 lbs) dry weight/power source <1.5 L (0.05 ft^3)	• 30 day continual operability • 20–100% RH • 35–120 °F	Use passive or alternative energy

An important distinction between the requirements for the USMC PWPS and the smaller SWPS/LNWPS is that the former is required to purify freshwater, brackish water, and seawater sources, while the squad unit system is only required to purify fresh or brackish water (up to 5 g/L) (**Table 2**). Another important distinction is that the USMC SWPS/LNWPS states a preference for a man-powered device. The preference for a man-powered device will ultimately limit the operational salinity range of the SWPS/LNWPS. In a man-powered system, it is unrealistic to supply the pumping power needed to overcome the osmotic pressure of 35 g/L seawater, but it is more feasible to achieve the modest pressures required to treat brackish water.

Any system intended to treat seawater will require an external power supply, even if human powered is the stated preference. Nonetheless, the power requirements stipulated for small-unit and individual devices remain loosely defined, and the successful development of new DoD potable-water technologies would benefit from the establishment of more specific volumetric and gravimetric energy/power consumption targets that are based on anticipated power sources available in the field. A higher priority should be given to technologies able to run on conventional batteries or small generators as well as technologies that can be interfaced with energy-harvesting approaches, such as solar-driven technologies. In conjunction with the establishment of such power/energy benchmarks, laboratories assigned with validation of new technologies should develop standard tests that account for energy consumption in practical prototype devices.

Figure 6. A Platoon Water Purification System (PWPS) operated by Marines at Camp Lejeune, NC (U.S. Marine Corps photo by Lance Cpl. Sixto Castro).

In contrast, the physical requirements of all these small unit devices are highly specific and comparable in that they are all obliged to be compact and man-portable, commensurate with the number of individuals they service. Weight requirements are determined by standard limits for one- and two-man lifts. Size restrictions for system components or full devices are based on the storage space of a sustainment pouch, assault pack, or the cargo space of a lightweight vehicle. With force mobility and agility being the ultimate goal, there is little room for compromise on the size and weight restrictions of water-treatment devices.

Beyond SWaP requirements, other important design criteria and operational criteria are also important for small-unit water purification. Water technologies must have fast throughput so the mobile warfighter can produce a day's worth of potable water in limited time (Table 2). The water-treatment device should have a minimal detectable signature, (acoustic, thermal, or electromagnetic). As water-purification units are scaled to smaller sizes, they must still be fabricated with robust architectures to survive anticipated mechanical stresses and continue their function, while minimizing weight and volume burden.

New water-purification systems should be versatile in processing variable input-water compositions (*e.g.*, different salinity) and also have the ability to function over a wide range of water temperatures and ambient temperatures. Historically, DoD water-purification strategies have relied on chemical additives for treatment and/or quality testing as part of the process to achieve potability standards, but these consumable supplies pose an additional logistics burden. New technologies that mitigate the need for such consumable supplies are highly desirable. In addition to meeting the physical and chemical potability standards outlined in TB MED 77, the treatment technology should have the versatility to handle contaminants of emerging concern that may be encountered in a practical setting, but have yet to be added to the growing list of TB MED 77 standards. From a practical standpoint, new water-purification systems should require minimal training to use and be low-maintenance, factors that would free personnel to fulfill other critical tasks of the designated mission.

2.3. Emerging Technologies and Remaining Gaps

Recent investments are driving significant progress in the development of water-treatment devices that meet the operational requirements and design criteria for small unit/individual systems. Scaled-down RO systems are the most mature treatment technology, and have thus far been the most successful. Other promising technologies, including electrochemical approaches or solar-thermal approaches, have been identified, but have yet to ascend to higher technology readiness levels (TRL). At the time of this report, the USMC PWPS is the smallest-scale RO devices that has been fielded,[4] whereas an SWPS/LNWPS scaled-down RO unit is still in development.[19]

In 2020, the prototype PWPS units built by the Parker Hannifin Corporation (**Figure 6**) passed verification testing[20,21] and has been subsequently fielded by the USMC.[4] The scaled-down RO system achieves impressive performance courtesy of three key innovations: 1) a lightweight prefiltration media that eases the burden on the downstream RO process; 2) an energy-recovery device; and 3) a light-weight, encapsulated carbon fiber RO membrane, which reduces the weight relative to typical reinforced pressure vessels. The units operate at an energy efficiency commensurate with the larger ROWPUs (**Figure 4**).

A Phase II SBIR contract was issued to Triton Systems Inc. in October 2020 to build prototype SWPS/LNPWPS devices.[22] The SWPS/LNPWPS is a redesigned version of a commercially available, man-powered desalination device. An example of an emergency desalination device is the Katadyn Survivor 35 hand-powered RO water treatment device (**Figure 7**).[23] The Phase II description summarizes innovations the Triton Team will pursue to improve the performance of existing portable RO systems to achieve 24 ounce per minute production from brackish water.[22] The improvements include the use of an anti-fouling coating that reduces fouling and increases permeability and the integration of an energy recovery feature that aids in pressurization of the stream. Even if the effort is successful, the production rates are at the low-end of acceptability (**Table 2**), and water generation is labor-intensive and time-consuming for the user. [22]

Figure 7. Photograph of the Katadyn SURVIVOR-35, hand-powered RO water treatment device. Photograph available online at https://www.katadyngroup.com/us/en/8019948-katadyn-survivor-35~p6775.

As a result of the recent SBIR programs, the USMC has fielded a scaled-down RO system that satisfies platoon-scale operations, but there remains a need for individual and squad-scale production devices that do not require fresh or brackish water inputs. At these smaller scales, RO is limited by the size and weight of pumping components, although it is still at present unrivaled in terms of power consumption, reliability, and versatility. The search for viable squad and individual-scale treatment devices must be expanded beyond scaled-down RO to consider emerging technologies at lower TRL. While other technologies may not yet rival RO in terms of power consumption, they have the potential to be more compact and lightweight, and thus may be more suitable to expeditionary deployment, particularly if they are self-powered. Other desalination technologies for small-scale devices that have received research investment from the USMC, U.S. Army, and DARPA, include:

- Capacitive deionization[24,25] and hybrid capacitive deionization[19]
- Alternating-current RO and alternating-current capacitive deionization[17]
- Desalination batteries[16,17]
- Atmospheric Water Harvesting[18]
- Forward osmosis[24]
- Solar-thermal approaches (plasmonic heating membrane-assisted distillation)[16]
- Ion concentration polarization devices (ARO-ISN UARC)[26]

In the ensuing sections of this report, we discuss the aforementioned technologies and related approaches from the scientific literature, organized according to whether the driving force for desalination is supplied by pressure, electrical, or solar input. We describe the mechanism of water purification and evaluate prospects for effective device design. In our evaluation, we consider energy efficiency, scalability, reliability, and ease of operation amongst the criteria we used to identify promising technologies. Technologies are assessed with respect to their applicability for small-scale water supply with a specific focus on desalination function. ***Because there is not a large commercial market for this scale of water-treatment device, and other U.S. government agencies (e.g., Department of Energy, Bureau of Reclamation) are focusing efforts on large-scale systems, the vast majority of innovation for small-scale treatment has been and will continue to be driven by DoD investment.***

Thermal-driven (e.g., distillation) and pressure-driven (*e.g.*, RO, forward osmosis) strategies face inherent limitations in energy efficiency and scalability, respectively. Therefore, we focus mainly on electrochemical approaches to desalination as the most promising technology ready to ascend the TRL scale to a level suitable for small-scale DoD applications. Although electrochemical desalination technologies, including CDI, have been evaluated by the USMC and Army previously, there have been significant game-changing technological advancements in the past 5–10 years, including new materials development and device configurations, that warrant further consideration.

We also focus on AWH as another promising avenue for water generation. This technology has the potential to extract water from humid air in most climates on the globe. Although, at present, AWH has low production rates and is highly energy intensive, ***the unique ability of this technology to function independent of a freshwater or saline water supply is a key advantage that makes AWH worthy of further attention.***

3. TECHNOLOGY ASSESSMENT

3.1. PRESSURE-DRIVEN DESALINATION: REVERSE OSMOSIS & FORWARD OSMOSIS

3.1.1. Reverse Osmosis

As noted above, RO systems have received significant investment to date and have proven their value for potable-water generation, particularly at large scales (base-camp, vehicle-mounted). As such, their development is highly mature, but RO is still the benchmark by which all technologies are compared. Reverse Osmosis is a pressure-driven process, where saline water is pressurized against a selective membrane that allows water molecules to permeate while rejecting dissolved solids and ions (**Figure 8**). A pressure exceeding the osmotic pressure of the feed solution is applied to drive water through the membrane. The minimum required pressure is proportional to the total dissolved salt content of the brine solution according to the Van't Hoff equation. Additional pressure is required to ensure adequate flow rate and to overcome pressure losses in the system, including membrane resistance.[27,28] The recovery ratio is the ratio of permeate flow rate to the feed flow rate, and can also be expressed in terms of percent recovery. The theoretical minimum specific energy required for desalination depends upon the input salinity, water-recovery ratio, and salt-rejection ratio (**Figure 9**).

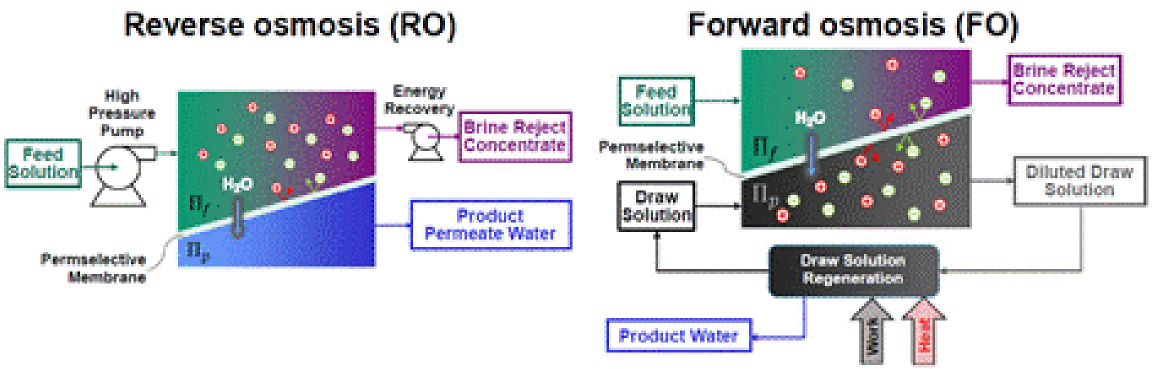


Figure 8. Flow diagrams for reverse osmosis (left panel) and forward osmosis (right panel). Reproduced from J. J. Urban, *Joule* 1 (2017) 665–668. Copyright 2017, Elsevier. DOI: 10.1016/j.joule.2017.10.002.

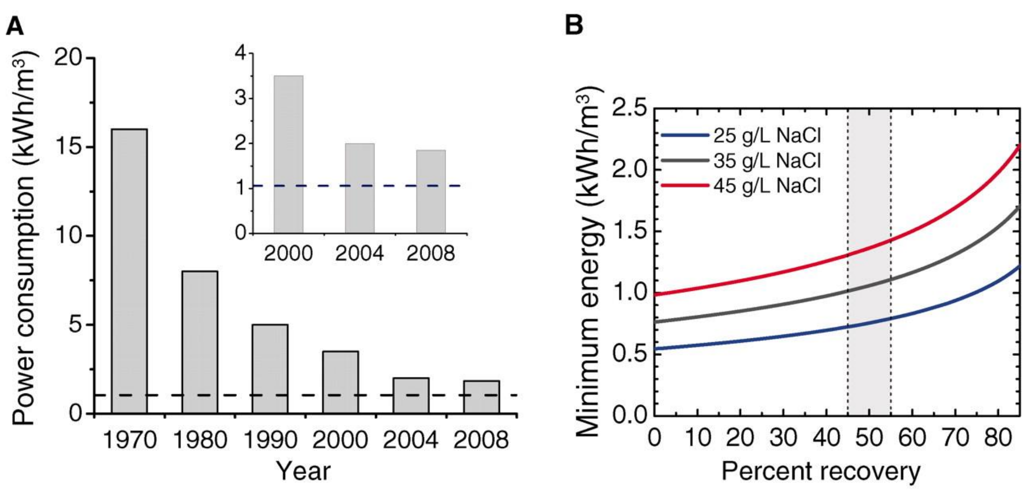


Figure 9. (A) the evolution of power consumption for the reverse osmosis step of seawater treatment plants from the 1970's through 2008. The theoretical minimum energy required for desalinating seawater is indicated with dashed line (1.06 kWh/m^3). **(B)** the theoretical minimum energy for desalination as a function of percent recovery for less saline seawater (26 g/L), average salinity seawater (35 g/L), and hypersaline seawater (45 g/L). Reproduced from Elimelech *et al.*, *Science*, 333 (2011) 712–717. Copyright 2011, American Association for the Advancement of Science.
DOI: 10.1126/science.1200488.

Reverse osmosis is the most widely utilized desalination technology for municipal or industrial water supply because it is the most efficient, reliable, and versatile. Energy consumption, mostly attributed to pumping costs, remain the primary operational cost of RO, although pre- and post-treatment also contributes to energy consumption. As such, the actual energy requirement for RO seawater desalination is several times higher than the theoretical minimum (**Figures 4, 9**).

Several recent reviews have thoroughly detailed technological advances in RO and other desalination technologies.[27,28] Efficiency improvements in RO have come from four main areas: *i*) implementation of energy-efficient pumps and energy-recovery devices; *ii*) advanced membrane designs to hinder fouling, increase water-salt selectivity, and increase water permeability; *iii*) advanced process control to optimize for system flow-rate, salinity, and temperature; and *iv*) better pre- and post-treatment, namely a shift from media filtration to micro- and ultra-filtration. As a result of these advancements, the efficiency of RO plants has improved dramatically over the past 5 years and has come closer to its thermodynamic minimum of 1.1 kWh/m^3 at 50% water recovery (**Figure 9**).[29]

Although RO systems are the best option for municipal and industrial supply, there are inherent limitations for scaled-down, lightweight systems. Like all membrane processes, membranes are prone to fouling. The high cost and energy associated with high-pressure pumps limits small-scale applications, and small-scale RO units have a much higher specific energy consumption. The mobile ROWPUs and PWPS require 2–10 $\times$ more specific energy per volume potable water produced relative to municipal RO plants (**Figure 4**). Nonetheless, advances in RO are worth monitoring even as we consider alternatives.

3.1.2. Forward Osmosis

Forward osmosis (FO), like RO, utilizes water transport across a selective membrane to separate salt from water. In forward osmosis, a concentrated “draw” solution generates the osmotic pressure to pull water from seawater across the membrane (**Figure 8**). The draw solute must then be separated from the diluted draw solution and recycled. Because high pressure is not needed to drive water across the membrane, the system operates at atmospheric pressure and avoids several pitfalls of high-pressure RO systems, namely, the large energy consumption from high-power pumps and an increased chance of membrane fouling. The system can be more lightweight than an RO system without the need for structural reinforcements necessary in high-pressure components.

The utility of FO is ultimately limited by the search for an effective draw solution, as the production rate and efficiency of this process is related to the osmotic pressure of the draw solution and the ease with which the solute can be recycled. Commonly, volatile solutes (ex. SO_2,

NH_3/CO_2) are utilized because they can be distilled from the diluted draw solution with modest heating, and subsequently reused.[27,30] Easily precipitable salts are another option because they can be separated with modest pH adjustments. Solute recycling can be eliminated altogether if a concentrated, consumable solute solution is continuously added to the process, such as fructose- or glucose- based concentrates.[27,30]

No matter the approach, the need for a draw solution inherently limits the scalability of FO as the mass and volume of the draw solutions contribute significantly to system size and weight. The use of precipitants or concentrated draw solutions contribute to consumables burden. Glucose- or fructose-based concentrates can be used as consumable solutes, but increase the consumables burden, while adding a sweet taste to the final product and negatively impacting human health for prolonged consumption. Although the energy consumption of the desalination step is minimal because high pressure is not needed, the energy consumption associated with draw solution recovery increases the overall power consumption to levels commensurate with RO.[27] Given the aforementioned limitations, along with the fact that FO is a relatively slow, low-throughput process, FO is unlikely to be appropriate for small-unit or individual water treatment devices.

3.2. Electrically Driven Desalination

Although electrochemical methods are not as widely utilized as RO for large-scale desalination, electrochemical desalination may offer more flexibility than pressure-driven methods in terms of designing for smaller scale. For example, individual two-electrode electrochemical desalination cells can be assembled into multicell stacks and modules to achieve the degree of salt removal and volumetric throughput for a particular application. Electrochemical techniques do not require high pressure and obviate the need for heavy and power-intensive pumping because potential differentials drive migration of charged species. There are also several variants of electrochemical desalination technologies that can be subdivided according to how the potential differential is established and whether ions from the salt solution are simply transported, diverted, or captured in an electrode, thus offering additional design flexibility depending on desired feed-source composition or operating conditions.

While the proceeding discussion focuses primarily on general desalination, electrochemical methods have also been developed for specific removal of toxic heavy metals from aqueous media.[31] For example, there are multiple electrochemical routes (capacitive capture, electrocoagulation, electro-Fenton reactions) for mitigating arsenic,[32] which may arise from either natural or man-made sources, and is a contaminant of high DoD interest for removal from environmental sources used in potable-water generation.[4] We also note also that many of these electrochemical cell configurations and electrode materials can be used for "salinity-gradient energy" (SGE) harvesting, essentially the reverse process of desalination.[33,34] Thus, if water sources of differing salinity are available (*e.g*., seawater versus inland brackish water), these electrochemical desalination systems may be used to generate moderate amounts of power for local use.

3.2.1. Capacitive Deionization

Capacitive deionization is an electrochemical approach to desalination that is based on electrostatic storage of ions at the surfaces of porous electrodes.[35,36,37] Under the application of an electrical bias across two opposing electrodes, achieved with either applied voltage or current, ions in the contacting solution between them are attracted to electrode surfaces of the opposite polarity. There they adsorb in the electrical double layer until the bias is released, thereby reducing the effective salt concentration of the contacting water feed (**Figure 10**). This electrosorption process is essentially analogous to "charging" an electrochemical capacitor (*i.e*., "supercapacitor"). Once surfaces become saturated with ions, the cell must undergo a regeneration cycle where adsorbed ions are then released (forming a stream of higher salinity), and the cell made ready for a subsequent desalination cycle. Electrochemical discharge during regeneration releases energy that can be partially recycled to assist in powering adjacent cells undergoing their electrosorption step if a multicell stack design is used. Depending on device design, >50% energy recovery can be achieved in such a fashion, ultimately reducing overall energy consumption for CDI operation, and compensating for the more complex cell design required.

Membrane capacitive deionization (MCDI) is an alteration to traditional CDI in which complementary ion-exchange membranes (IEMs) are placed at each of the opposing electrodes to minimize counter-ion adsorption, resulting in higher desalination capacity per cycle and greater overall energy efficiency (**Figure 10**). This enhancement in performance comes with the added costs, fouling challenges, and kinetic limitations associated with using IEMs, but MCDI remains a design of significant interest for electrochemical desalination.[38]

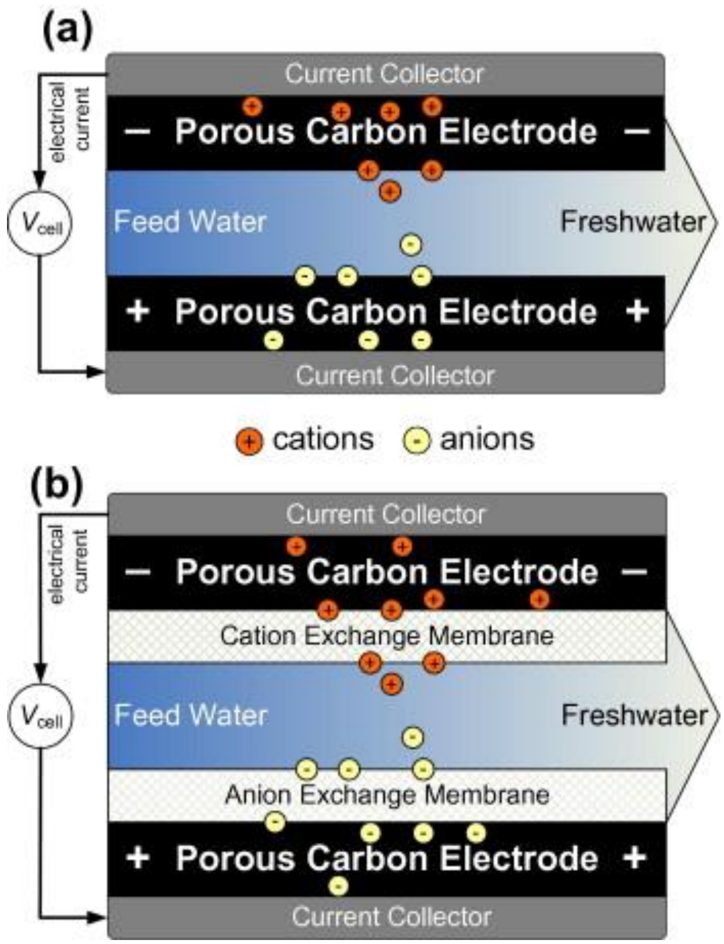


Figure 10. Schematic of CDI and mCDI devices for desalination. Reproduced from Porada et al., *Prog. Mater. Sci.* 58 (2013) 1388–1442. Copyright 2013, Elsevier. DOI: 10.1016/j.pmatsci.2013.03.005.

Many types of porous/nanostructured carbons have been used as active electrode materials for CDI, beginning with activated carbons due to their widespread commercial availability and high specific surface area for ion adsorption. Another early contender for CDI applications was carbon aerogels, which distribute their high surface areas in through-connected pore structures of desirable sizes for water transport and ion capture.[39,40] Carbon aerogels are also readily fabricated in monolithic forms that mitigate the need for additional binders in electrode construction. More recently, advanced forms of carbon such as nanotubes[41] and graphene-based materials and architectures [42] have also been explored for CDI.

One of the advantages of carbon-based CDI systems is that the ion-capture mechanism is primarily physical adsorption, with minimal associated chemical reaction. Thus, such systems are durable and have long operational lives if voltage is limited to avoid carbon corrosion. Yet the reliance on surface-sited ion adsorption in the electrical double-layer also limits desalination capacity (typically <20 mg/g), ultimately restricting the salinity range over which traditional CDI is competitive with RO in terms of energy consumption. For example, at a feed salinity of 2 g/L (low brackish range) and otherwise optimized operating conditions, the specific energy consumption of a CDI system would be on the order of 0.85 kWh/m^3 versus 0.09 kWh/m^3 for a typical RO system, as noted by Qin et al.[43]

3.2.2. Faradaic Deionization

To overcome capacity limitations with conventional CDI and make electrochemical desalination more competitive, researchers have turned their attention to the use of redox-active materials for ion capture. Such approaches have been generally denoted as "Faradaic deionization" (FDI) or "Intercalative deionization" (IDI).[44,45,46,47,48,49,50] The active materials used in these configurations typically undergo coupled ion/electron-exchange reactions, analogous to the charge-storage mechanisms that are operational in many batteries and pseudocapacitance-based electrochemical capacitors. Because these reactions involve electron transfer and concomitant changes in material oxidation state, a larger concentration of counter-balancing ions may be stored at, or even within the bulk, of such materials, resulting in significantly higher capacity than that achievable at the surface-confined double-layer of carbon electrodes. **Figure 11** shows how the use of faradaic/intercalative materials has transformed the performance of electrochemical desalination over the past few years. Note that the carbon materials described above may still be included in the overall electrode structure to enhance electrical conductivity and provide a host structure for the active (ion-storing) material, or may also be paired as individual capacitive electrodes against faradaic electrodes in an asymmetric configuration (*i.e.*, "hybrid capacitive deionization"; HCDI).

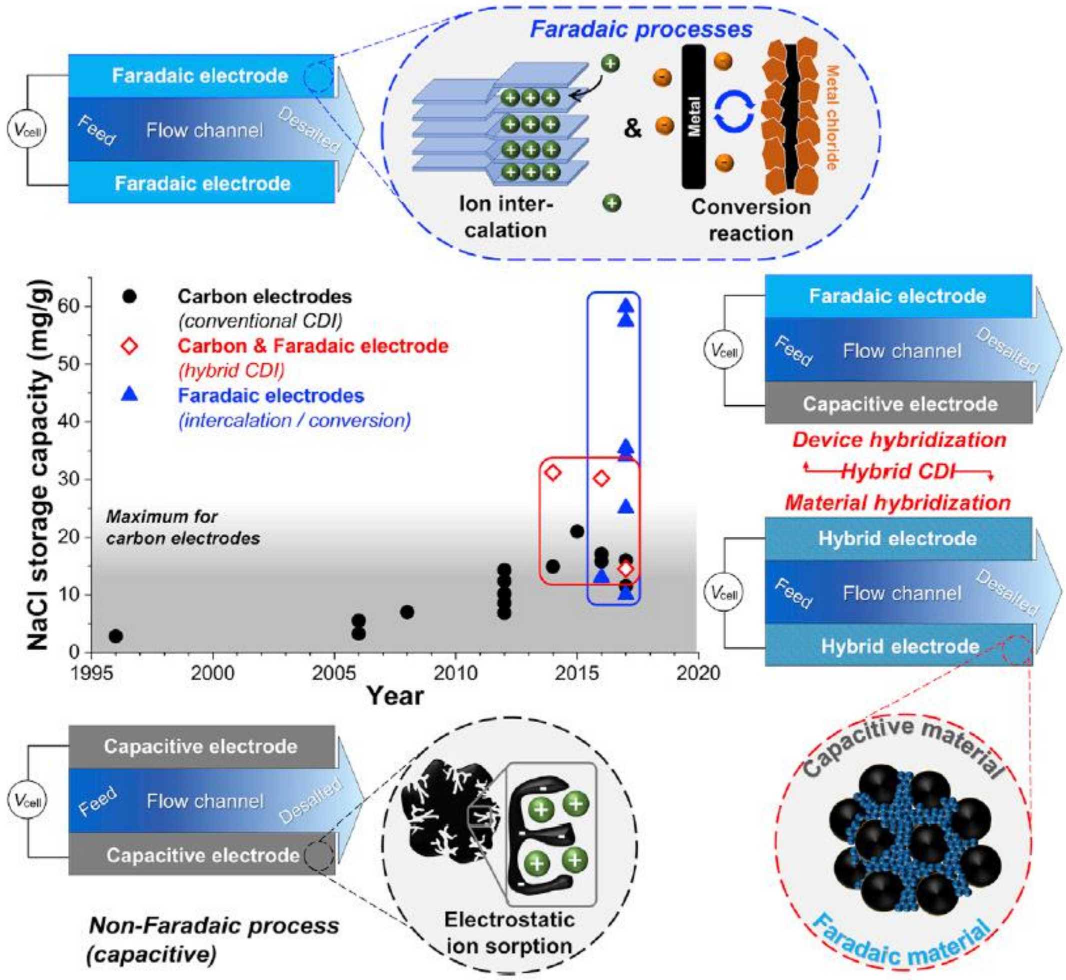


Figure 11. Schematic of capacitive versus Faradaic mechanisms for desalination and their relative performance for NaCl removal. Reproduced from Suss et al., *Joule*, 2 (2018) 10–15. Copyright 2018, Elsevier. DOI: 10.1016/j.joule.2017.12.010.

Over the past decade, many different types of both organic and inorganic Faradaic materials have been investigated to enhance ion-uptake capacity in electrodes designed for FDI. Redox-active polymers were among the first such materials investigated for desalination and selective ion-capture purposes.[51,52] Manganese oxides (*e.g.*, $Na_4Mn_9O_{18}$)[53] were quickly adapted to FDI/IDI, borrowing from their successful development for energy-storage applications (Na-ion batteries and aqueous electrochemical capacitors). Hexacyanometallates (*e.g.*, Prussian Blue),[54] polyanionic compounds (*e.g.*, $NaTi_2(PO_4)_3$),[55] and transition metal carbide-based compounds ("MXenes")[56] are other inorganic candidates that have demonstrated promise for FDI/IDI. Many such materials have redox mechanisms that are specific for cation uptake (mainly Na^+), while materials designed for anion capture are fewer in number. Silver[57] and bismuth[58] have been examined for such purposes, with the reversible electrochemical formation of the corresponding metal chloride or oxychloride as the active mechanism for Cl^- removal. Certain electroactive polymers, such as pyrrole, also exhibit anion-specific capture mechanisms,[59] but the further development of anion-capturing Faradaic materials is warranted to enhance the performance and applicability of FDI/IDI.

Faradaic materials have demonstrated advantages over high-surface-area carbons in terms of ion-capture capacity. While the double-layer capacitance mechanisms of carbons typically limit desalination capacity to < 20 mg/g, Faradaic electrode materials support capacities from that value to >130 mg/g.[49] ***Higher ion-capture capacity translates to either more volume desalinated in a given cycle or the ability to process higher-salinity water feeds.*** Because the associated redox reactions operate at slower timescales due to solid-state diffusion and electrode kinetics limitations, the advantages of higher desalination capacities are partially offset by lower desalination rates for many FDI/IDI configurations (typically < 0.3 mg/g/s).[49] In the scientific literature, performance metrics in terms of rate are commonly expressed in "Kim-Yoon" plots of deionization capacity (mg/g) versus mean deionization rate (mg/g/s; see **Figure 12**),[60] which are the equivalent of "Ragone" plots (energy versus power) used to benchmark the performance of batteries and electrochemical capacitors. In order to make Faradaic-based deionization techniques viable in terms of production rate, additional development of Faradaic/intercalative materials should focus on enhancing ion-uptake kinetics under practical desalination conditions, for example by expressing the active material in nanostructured forms that reduce ion-diffusion distances and specific crystalline or disordered forms that increase solid-state diffusion coefficients.

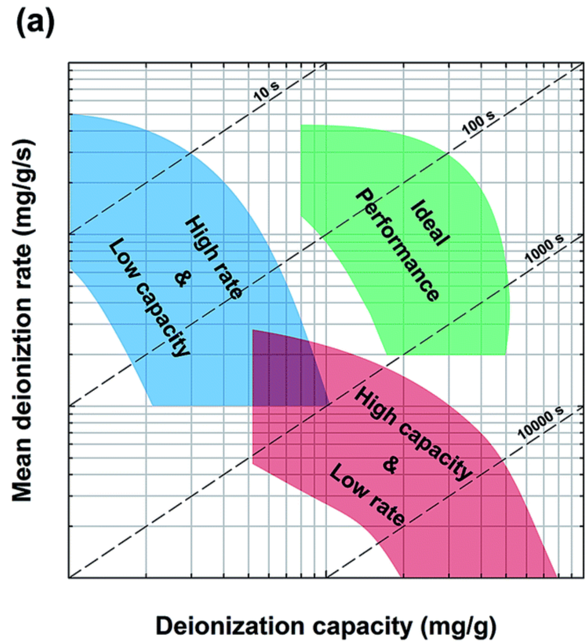


Figure 12. A conceptual diagram of a CDI "Kim-Yoon" plot, as initially proposed by Kim and Yoon (reproduced from *RSC Adv.* 5 (2015) 1456–1461). Copyright 2015, Royal Society of Chemistry. DOI: 10.1039/C4RA11257A.

Faradaic materials are further distinguished from their carbon counterparts by cation- versus anion-specific capture mechanisms, as noted above. This specificity is advantageous for minimizing counter-ion adsorption effects, but also requires more complex device configurations that pair complementary electrodes (and sometimes IEM components) in order to realize effective desalination (**Figure 13**). For example, HCDI device configurations replace one of the carbon electrodes of a conventional CDI cell with a Faradaic/intercalative electrode.[61] Device-level desalination metrics are increased compared to CDI analogs due to the higher capacity of the Faradaic/intercalative electrode, but the capacity imbalance between the opposing electrodes ultimately limits performance. To achieve higher desalination capacity, the same Faradaic/intercalative electrode may be used on both sides of the cell if an anion-exchange membrane is placed between them, in a configuration that has been dubbed "rocking chair capacitive deionization" (RCDI). Pairing complementary cation- and anion-intercalating electrodes (*e.g.*, $Na_{0.44}MnO_2$ and Ag electrodes, respectively)[61] yields a "dual-ion intercalation electrochemical desalination" (DEDI) cell configuration. The former two configurations exhibit higher capacities than HCDI due to the use of two Faradaic/intercalative electrodes, while the symmetric nature of the RCDI cells generally yields higher desalination rates.

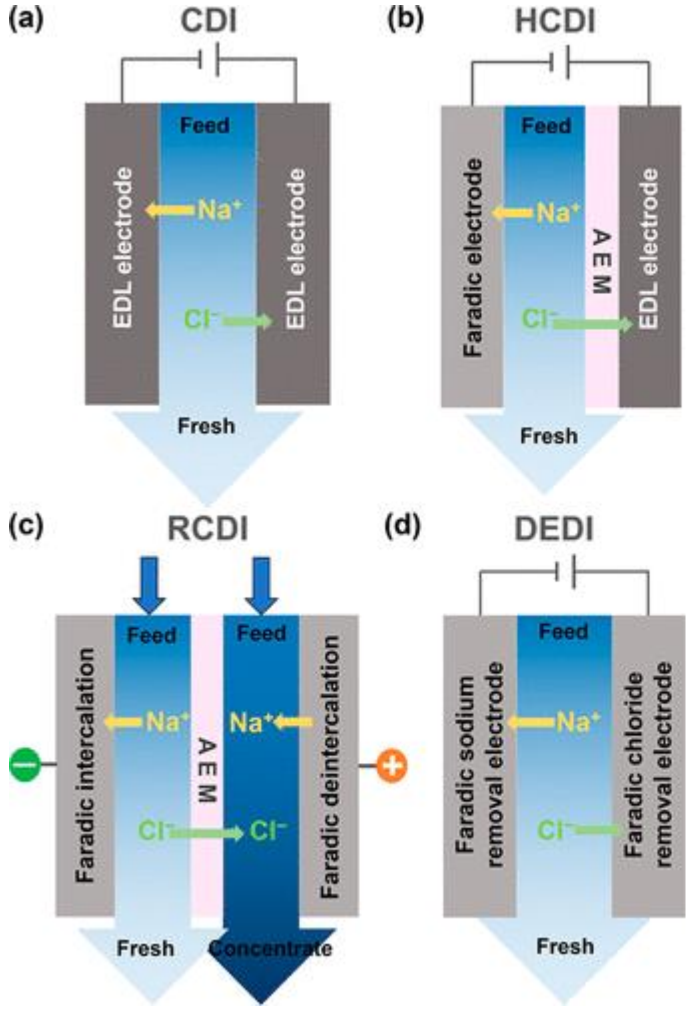


Figure 13. Schematics of different cell configurations for capacitive and Faradaic variants of electrochemical desalination. Reproduced from Liu et al., *ACS Nano* 15 (2021) 13924–13942. Copyright 2021, American Chemical Society. DOI: 10.1021/acsnano.1c03417.

The various performance characteristics and device designs described above impact another important metric for desalination—energy efficiency. Metzger et al. published a detailed analysis comparing the projected energy efficiency of various types of electrochemical desalination schemes versus RO.[15] Their results are captured in **Figure 14**, which projects energy consumption in terms of Wh of energy per L of water produced versus feed water salinity for several of the above approaches. In the brackish salinity range, each electrochemical approach shows some degree of advantage over RO with respect to energy input, but only modestly so for HCDI, while MCDI extends to the high end of the brackish range. More promising is the trend predicted for "IDI" (generally for cells with two redox-based electrodes), which may extend the practical salinity range of electrochemical techniques to seawater concentrations, although such has yet to be demonstrated at scale in practical systems. The analysis of Metzger et al. supports the feasibility and competitiveness of advanced forms of electrochemical desalination over a wider range of salinity than previously attainable with conventional CDI. Such projections also account for energy-recovery schemes in which CDI and/or FDI/IDI cells act effectively as electrochemical capacitors or batteries in storing energy during one or the other of their half cycles, a fraction of which can be tapped to power complementary cells within a multicell stack. Percent energy recovery is generally higher with CDI-based approaches due to charge/discharge-hysteresis losses with many Faradaic materials,[62] but further optimization of FDI/IDI materials at the nanoscale and optimized pairing of electrode materials that comprise the desalination cell should narrow that gap.

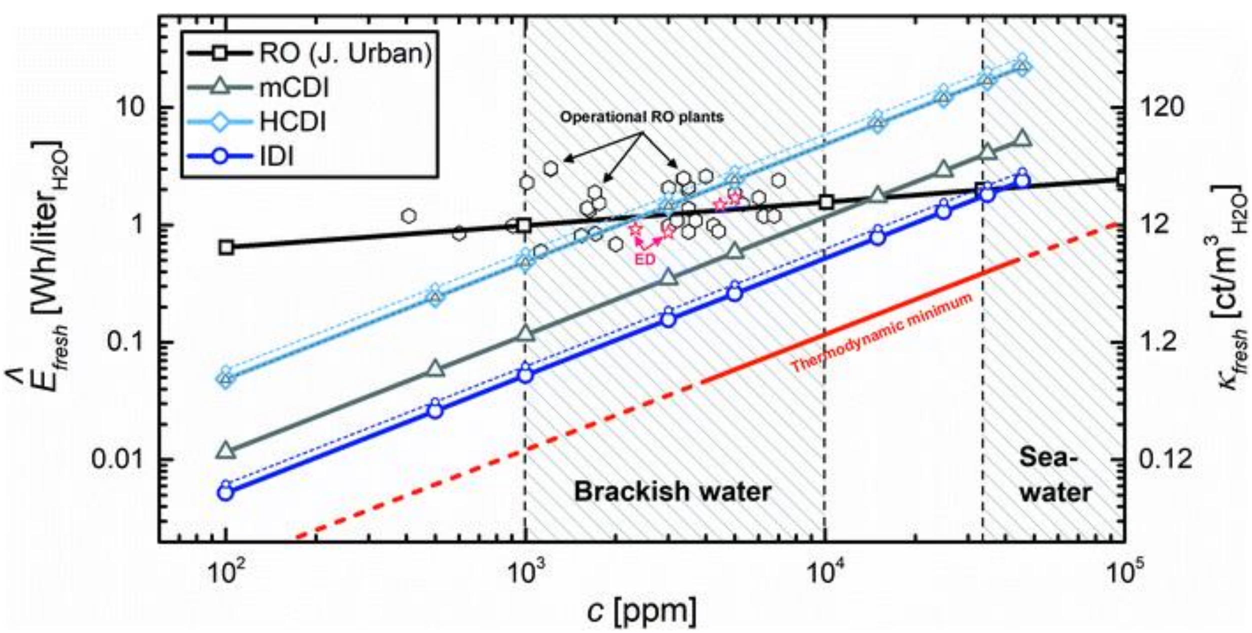
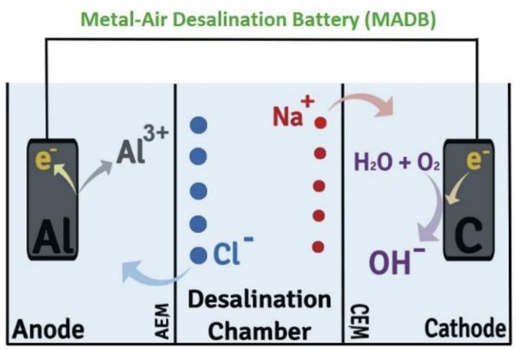


Figure 14. Conceptual plot of energy efficiency versus feed salinity for various electrochemical desalination approaches, as also compared with RO. Reproduced from Metzger et al., *Energy Environ. Sci.* 13 (2020) 1544–1560. Copyright 2020, Royal Society of Chemistry. DOI: 10.1039/D0EE00725K.

3.2.3. Metal–Air Desalination Batteries

The moniker, “desalination batteries”,[63] has also been used to describe desalination cells that have two battery-type electrodes (similar to DEDI and RCDI cells). One notable variant is the “metal–air desalination battery,” which comprises a metal anode (zinc, magnesium, or aluminum) and an air-breathing cathode.[64] In this configuration, desalination occurs while the battery discharges, as electrical current from the discharge drives ions (*e.g.*, Na^+ and Cl^-) from a central water-feed channel across complementary IEMs toward the opposing electrodes (**Figure 15)**.



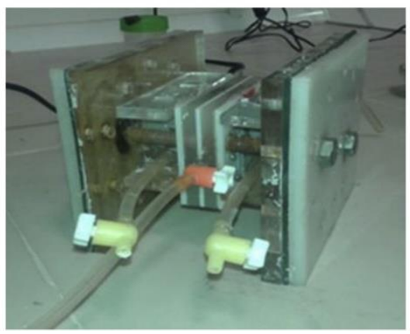


Figure 15. Schematic and photograph of an aluminum–air desalination battery. Reproduced from M. Ghahari et al., *J. Power Sources* 412 (2019) 197–203. Copyright 2019, Elsevier. DOI: 10.1016/j.jpowsour.2018.11.042.

Metal–air desalination batteries require no external power input for the initial desalination cycle and, in fact, provide net power that can used for other purposes. The energy needed to power desalination is already stored in the metal anodes, which are chosen for their ability to spontaneously oxidize in the metal–air cell. Anode oxidation is balanced by reducing molecular oxygen (harvested from air) at the cathode. Air-breathing cathodes can be relatively thin and lightweight, and get their oxidant from outside air, while other cathode candidates that rely on bulk reactions are heavier. Desalination then proceeds until the metal anode is electrochemically exhausted. "Regeneration" of a metal–air desalination cell typically involves mechanical replacement of the anode material with fresh metal in a foil or plate form. The disadvantage of this approach is the additional logistics burden of supplying and transporting replacement anodes on mission. Electrical recharging of metal–air desalination batteries is theoretically feasible, but as demonstrated through decades of research in the battery community, many technical challenges remain to achieve rechargeable metal–air batteries in practical and functional forms.[65] Nevertheless, Dai et al. have recently reported some early-stage progress with a rechargeable zinc–air desalination battery prototype.[66] Further advances in air-cathode performance and metal anode stability/cyclability may yet be adapted from the energy-storage research community to extend these promising metal–air desalination battery approaches with additional recharging function.

As noted above, the Army has recently sponsored early-stage desalination battery developments efforts for this promising approach.[16] Lynntech, Inc. received SBIR funding from the U.S. Army under SBIR A18-149 to adapt their metal–air desalination battery to suit the needs of the individual warfighter.[67] Their battery design aimed to meet U.S. Army targets for an individual treatment device, namely, the ability to achieve 1 L/h water production and to treat 135 L before maintenance at a total system weight of < 1 lb.[16]

3.2.4. Electrodialysis

Electrodialysis (ED) is an established deionization technology that shares some common features with conventional CDI (and variants thereof, as described above), also being driven by electrical energy input but achieving ion separation by different mechanisms.[68,69] A typical ED cell comprises two electrodes that are separated by multiple complementary IEMs, creating compartments for separating concentrated and diluted salt solutions (**Figure 16**). The application of an electrical bias across the membrane stack drives the transport of ions between channels. In cases where bipolar membranes (adhered AEM and CEM layers) are used in the cell stack, electrical bias across the two electrodes drives oxidization of water at the cathode (forming hydroxide, OH^-) and reduction of water at the anode (forming H^+). Charge neutrality is maintained by migration of complementary charged ions across the respective IEMs from the central feed channel to the electrode channels. Thus, ion concentrations decrease in feed channel and increase in the flow channels at the opposing electrodes. Electrode materials used for ED cells include some of the same high-surface-area carbons used for CDI and catalyzed metals (*e.g.*, ruthenium dioxide on titanium).

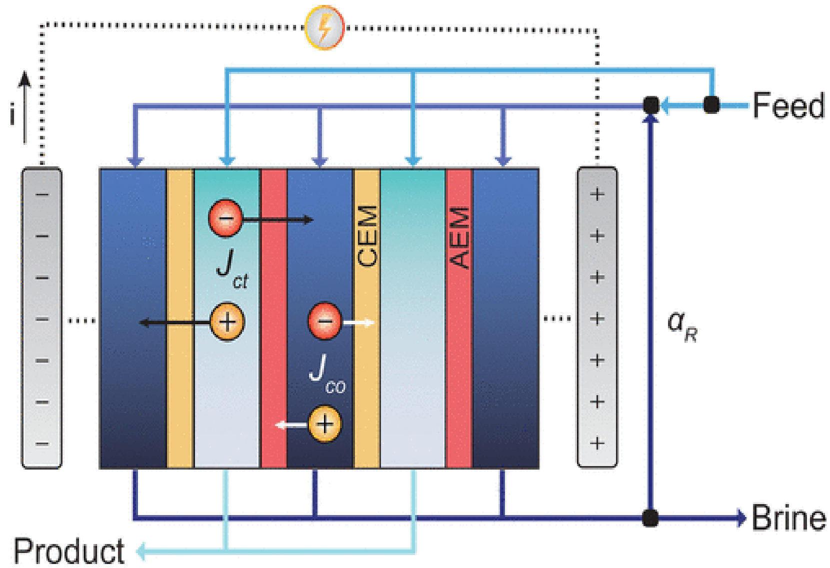


Figure 16. Schematic of a typical electrodialysis desalination system. Reproduced from Patel et al., *ACS ES&T Eng*. 2 (2021) 851–864. Copyright 2021, American Chemical Society. DOI: 10.1021/acsestengg.0c00192.

Electrodialysis is a relatively mature technology that is used in many industries for the selective capture of ionic species and water purification. General desalination efforts have focused on brackish waters (*e.g.*, groundwater or wastewater), with typical salinity levels in the range of 3 g/L, although one study posited the use of ED at salt concentrations up to 15 g/L.[70] Electrodialysis has the further advantages of high salt removal rates and the ability to run in batch or continuous modes. Typical energy consumption for ED ranges between 1 and 12 kWh/m^3, depending on feed salinity.[68] Patel et al. compared ED and RO and determined that ED was competitive or advantageous in terms of energy efficiency at salinity values <3 g/L, but RO is preferred at higher salt concentrations.[71] Membrane fouling is a major challenge for ED systems, leading to lower efficiency and increased maintenance costs.

3.2.5. Fuel-Cell Desalination

Closely related to ED is the relatively new concept of "fuel-cell desalination",[72] which utilizes the architecture of a conventional proton-exchange membrane fuel cell, but including complementary IEMs between the anode and cathode for salt separation (**Figure 17**). Instead of driving H^+ and OH^- formation at opposing electrodes with electrical energy input (as done with ED approaches), desalination fuel cells use H_2 fuel input at the anode and O_2 oxidant (supplied from air) at the cathode to drive the corresponding electrochemical reactions, that in turn, drive the separation of Na^+ and Cl^- across the internal IEMs. Like desalination batteries, electrical power is generated during the desalination step and is available for consumption by other devices. Desalination fuel cells can operate in continuous mode as long as hydrogen fuel is supplied. This technology may be of interest where hydrogen is readily available, but the logistics burden of containing and transporting hydrogen would discourage the use of desalination fuel cells for distributed small-unit operations.

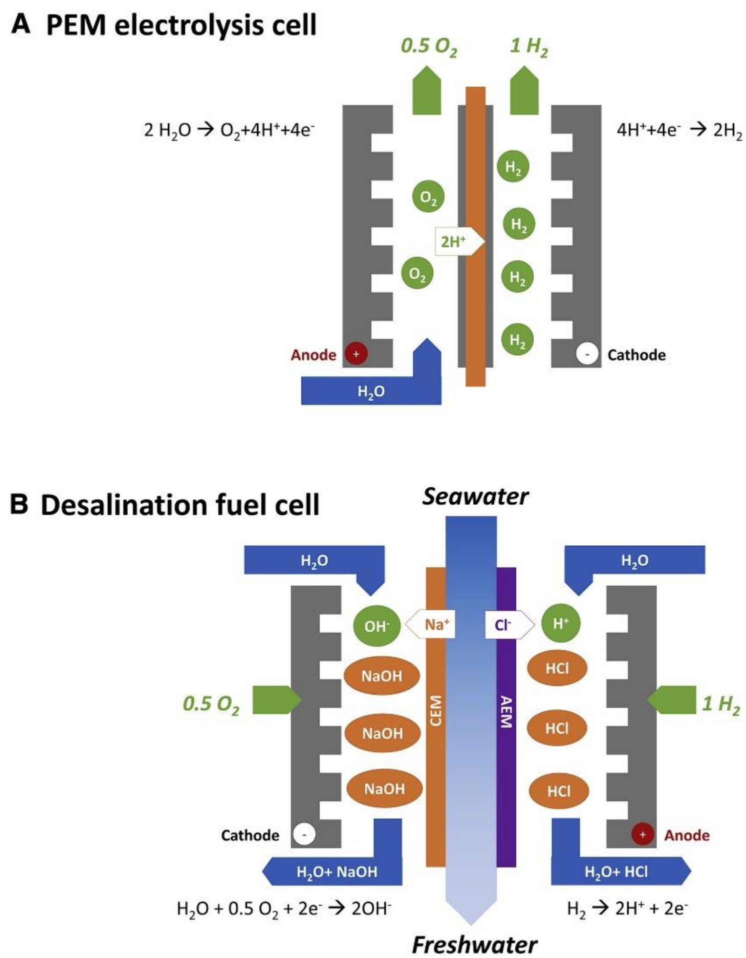


Figure 17. Schematic showing a (A) Proton-exchange membrane (PEM) electrolysis cell versus a (B) desalination fuel cell. Reproduced from Y. Zhang et al., *Cell Rep. Phys. Sci.* 2 (2021) 100416. Copyright 2021, Elsevier.
DOI: 10.1016/j.xcrp.2021.100416.

3.2.6. Ion Concentration Polarization

Ion concentration polarization (ICP) utilizes a separation mechanism that is indiscriminate for dissolved and suspended solids as well as metals and pathogens. The separation mechanism is based on a combination of electrochemical charge repulsion in conjunction with micro and nanofluidics. In ICP, a potential gradient established across an ion-selective nanochannel (typically cation selective) creates ion-depleted and ion-rich regions on either side of the nanochannel. The ion-rich region creates a repulsion zone near the junction of two microchannels wherein ions are repelled towards a microchannel that transports concentrated brine, while desalinated water passes through the charged region into the freshwater channel (**Figure 18**).[26,27,73] Because most suspended solids and pathogens also have a net-zero surface charge, the technique simultaneously removes suspended solids, bacteria, and viruses in conjunction with deionization. With this approach, high salt rejections and high water-recovery ratios have been achieved.

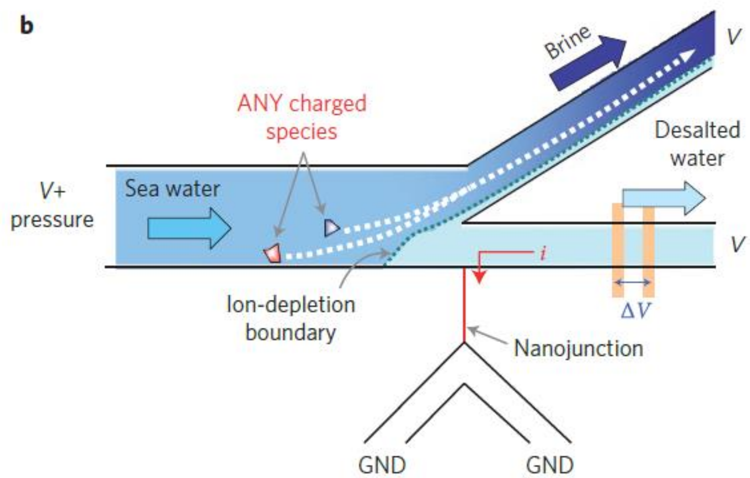


Figure 18. Schematic of an ICP cell. Reproduced from Kim et al., Nature Nanotech. 5 (2010) 297–301. Copyright 2010, Springer Nature Publishing.
DOI: 10.1038/nnano.2010.34.

Because ICP is not a pressure-driven process, there is no need for high-power pumping and ICP devices can be gravity fed. These devices typically only necessitate a cation-exchange membrane, and the elimination of an anion-exchange membrane greatly lowers costs and decreases fouling risks. There are many possible device configurations leveraging ICP, including single- and multi-stage desalination processes and single or multi-pass processes.

ICP devices were first demonstrated to desalinate seawater by Professor Jongyoon Han's group at MIT in 2010, but the specific power consumption for seawater desalination is expected to be much higher than the 3.5 kWh/m^3 that was reported in this initial demonstration.[73] Prof. Han holds several patents related to ICP desalination devices (*US patent 8,834,696 (2014); US patent No. 9,725,340 (2017); US patent No. 9,845,252 (2017))*.

Han et al. have utilized sequential ICP and ED treatment steps in a bench-scale prototype to leverage the fact that ICP is better suited for high salt concentrations and, in essence, also performs the "pretreatment" step of removing suspended solids. The downstream ED stage is then more optimized to produce potable water from the reduced salinity input. The estimated power consumption of the prototype multi-stage ICP/ED device is ~0.5–3 Wh/L for brackish water and ~16–27 Wh/L for seawater at a production rate of 1 L/h (**Figure 4**).[26]

Overall, ICP approaches offer several improvements over scaled-down RO for small-unit water treatment, being lightweight and not requiring high power consumption for pumping. The main limitation for ICP remains the slow water production rate, which may be challenging in circumstances where on-demand potable water is required.

3.3. Solar-driven Desalination

All of the water-purification technologies noted above require significant energy input to achieve effective output of water at desired production rates and purity levels. In the public and commercial sectors, there is a drive to exploit renewable energy to power large-scale desalination. Solar-powered desalination is the most prevalent approach, in part due to the convergence of fresh-water scarcity, seawater availability, and abundant sunlight in many areas of the world.[74] Sunlight can be harnessed for desalination either indirectly (conversion to electrical energy to power the various desalination/purification technologies noted above) or directly (*e.g.*, solar-driven evaporative processes).

3.3.1. Photovoltaic-Powered Desalination

The improving efficiency and decreasing costs of photovoltaic (PV) panels make this renewable-energy source attractive for desalination, with PV-powered RO systems being installed and evaluated at many locations in recent years. Photovoltaic technologies have also been developed, evaluated, and deployed as a portable power-source for small-unit expeditionary missions, with examples including the Ground Renewable Expeditionary Energy Network System

(GREENS) and Solar Portable Alternative Communication Energy System (SPACES, **Figure 19**). These fielded PV units could nominally be interfaced with portable RO or other desalination systems to provide necessary power. For example, a GREENS unit, which also includes an energy-storage component, provides 300 W power for 24 h after charging with 8 h sunlight (7.2 kWh stored energy). If 10% of that stored solar energy were diverted for desalination purposes, with a desalination system having an efficiency of 5 Wh/L, 144 L (38 gallons) of potable water would be produced.

Figure 19. U.S. Marine using a SPACES kit to power a communications system at King Faisal Air Base in Jordan (Marine Corps photo by Sgt. Christopher Q. Stone).

3.3.2. Direct Solar-Thermal-Evaporation Desalination

Alternatively, sunlight can be converted to thermal energy that drives evaporative processes for water purification (*i.e.*, "solar-thermal evaporation", "solar-thermal desalination"). Solar stills are the oldest and simplest of such technologies, where solar-heated water is distilled and collected as purified condensate. In a more modern approach, membrane distillation (MD) uses a porous hydrophobic membrane interfaced with a feed of solar-heated water on one side. Thermal gradients across the membrane drive evaporation and transport of water vapor to the cool side of membrane where condensed water is collected. This approach shows promise for desalination in areas with strong sunlight input.[75] As with simple solar stills, MD typically requires the setup of a solar concentrator or flat-panel thermal collector to heat the water supplied to the membrane. Further improvements in thermal-conversion efficiency are required to make such systems more competitive for use in the commercial sector.

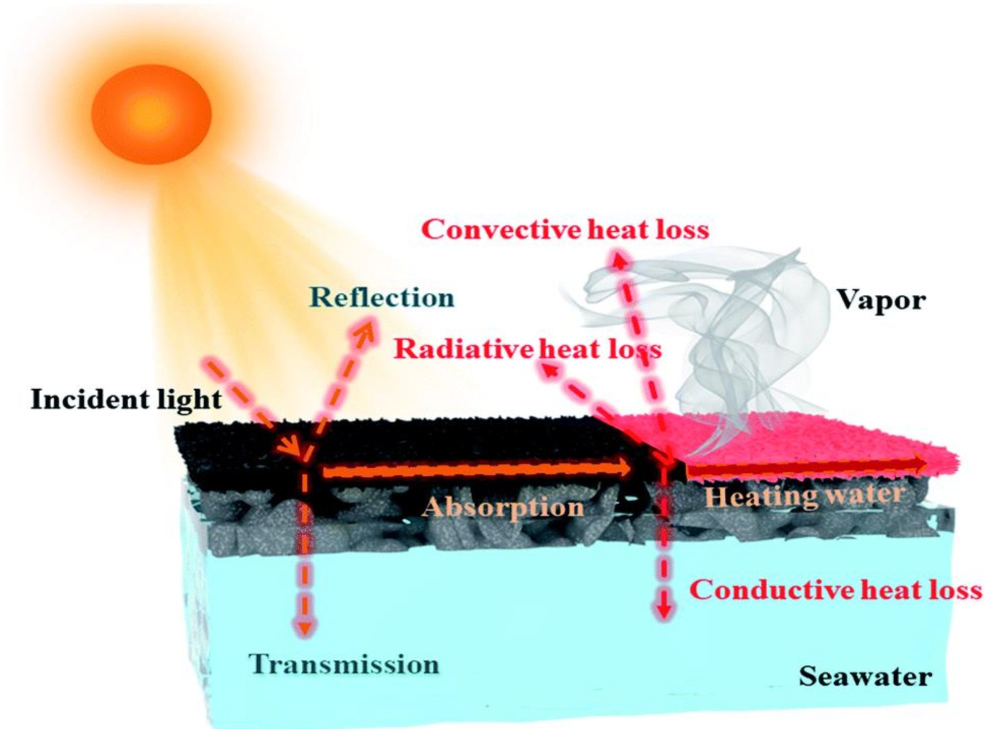


Figure 20. Schematic diagram of the design and function of an SDIE device. Reproduced from Liu et al., *J. Mater Chem. A* 8 (2020) 17907–17937. Copyright 2020, Royal Society of Chemistry. DOI: 10.1039/C9TA12612K.

Significant research is ongoing to develop advanced membranes that directly incorporate the solar-absorbance function to achieve "solar-driven interfacial evaporation" (SDEI),[76] ultimately eliminating the need for a separate solar-collection system (**Figure 20**). Many of these are based on engineered forms of porous carbons that may be functionalized to promote vapor transport and directed condensation.[77] Solar-to-vapor condensation efficiencies as high as 90% have been achieved in lab-scale experiments. Under optimized conditions, water output from a typical solar illumination of 1 kW/m^2 yields purified water output on the order of 1.5 $kg/m^2/h$.[76]

With the advances noted above, various solar-driven desalination technologies will become more common in the commercial market and perhaps also for use in remote areas for humanitarian efforts. Yet many challenges remain for their use in small-scale, mobile military missions, including: (*i*) low-to-moderate production rates; (*ii*) the large footprints that would be required for sufficient solar input; (*iii*) thermal signatures arising from solar-thermal methods; (*iv*) the need to operate in open areas; and (*v*) the intermittent nature of sunlight input.

3.4. ATMOSPHERIC WATER HARVESTING

Atmospheric water harvesting (AWH; alternately denoted as atmospheric water generation, AWG, and atmospheric water extraction, AWE) has emerged as a promising technology that can overcome the logistics challenges associated other water-purification technologies. The AWH approach is unique in that it does not require a primary liquid water source. Rather, AWH technologies facilitate the coalescence of atmospheric water, in form of droplets or vapor, into a supply of potable, liquid water. Atmospheric water is ubiquitous, accounts for up to 10% of the earth's freshwater sources (~ 50,000 km^3), and is replenished by the natural hydrolytic cycle.[78,79] Thus, AWH can be used for the sustainable production of drinking water, regardless of geographical or hydrological conditions. Moreover, water can be supplied in the event of contamination of existing water sources and other emergencies that disrupt water access. Atmospheric water harvesting is most effective and efficient where ambient relative humidity (RH) is moderate to high, whereas water-production rate and energy efficiency in dry climates may be challenging.

3.4.1. Passive Approaches to Fog and Dew Collection

There are various approaches to collecting atmospheric water. Early efforts on AWH mainly focused on fog/dew collection. In fog-collection devices, small water droplets condense on mesh-like structures into larger droplets that are collected in a reservoir via gravity or airflow.[80] The efficiency of such devices can be improved by accelerating the growth of water droplets on the collector surface and/or decreasing the critical water droplets size before falling from the surface. Researchers have demonstrated surfaces containing bio-inspired micro- and nano-structure features can exhibit enhanced and directed water transport properties.[81,82,83] Also, electrostatic interactions have been shown to increase the collection efficiency of fog meshes, albeit this approach increases the power requirements compared to passive systems.[84] Fog collectors are generally inexpensive and are capable of generating up to 12 L/m^2/day of water.[85] However, this technology is only practical in regions with high humidity (RH = 100%) and frequent fog occurrence and requires more extensive infrastructure and physical space to erect high-capacity fog meshes. Dew collectors also require a saturated local humidity at the condenser surface, but have an expanded operating range because they cool incoming air to lower its temperature below the dew point. In the simplest approach, passive radiative cooling dissipates heat from the condenser to initiate water condensation. Passive dew collectors require no additional energy input, but still only operate in high ambient humidity and water generation is slow (< 0.8 L/m^2/day).[85]

3.4.2. Active-Cooling for Enhanced Condensation of Atmospheric Water

Active-refrigeration techniques have also been employed to initiate condensation in dew collectors using conventional refrigeration technologies, such as vacuum compression refrigeration (VCR) or thermoelectric cooling (TEC). High-grade energy is required to power these devices, but they can efficiently collect atmospheric water at moderate to high temperatures (~20–40 °C) and relative humidity (45–100 %).[86,87] VCR-based AWH devices operate via the same principles as commercial refrigerators and air conditioners (**Figure 21**). Humid air is drawn into the evaporator chamber where it is cooled below its dew point temperature and condenses on the evaporator coils. These systems typically contain filters for the incoming air and water filters to purify the condensate. The water-generation rate depends on the system's cooling capacity, air-flow rate, and temperature and humidity of the incoming air.

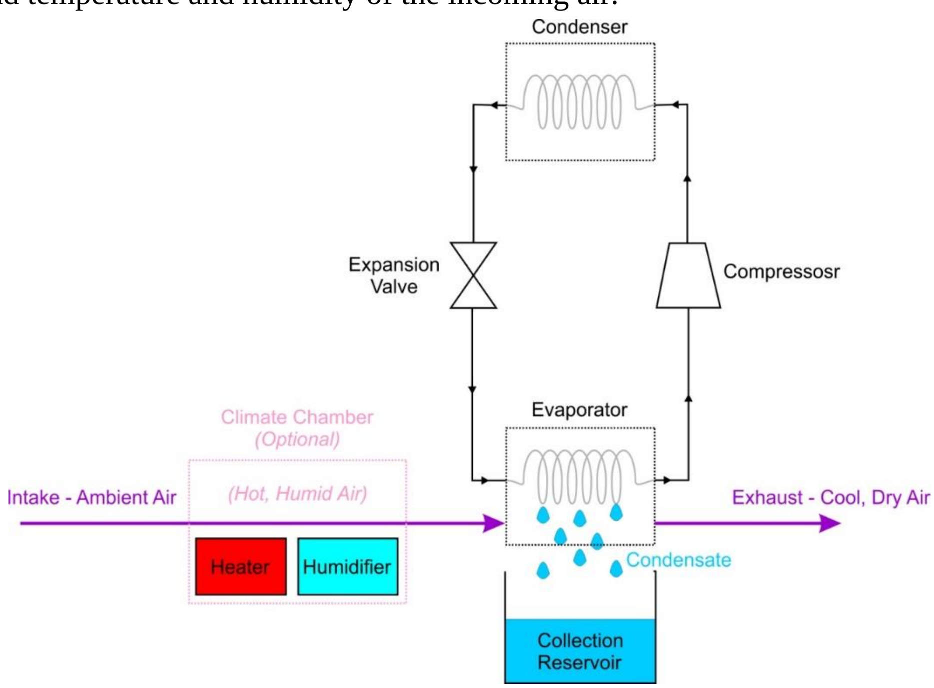


Figure 21. Schematic of active refrigeration system with optional climate chamber.

Because VCR-based AWH systems must cool large volumes of air, these systems are energy intensive and impractical at RH levels below 40% as the dew point of the incoming air approaches 0 °C. Optimal performance is achieved under hot and humid conditions. For example, Patel *et al.* reported a water generation rate of 1.78 L/h at 35 °C and 95% RH while consuming 0.75 kWh of energy per liter of water generated.[87] Climate chambers, which heat and/or humidify incoming air, have been incorporated to expand the operational range of VCR-based AWH systems and enhance water collection. For example, Tu and Hwang reported a water collection rate of 32.5 L/h while consuming 0.794 kWh/L of water using desiccant wheels to humidify incoming air and a heat pump system for heat recovery.[88] The most efficient use of these systems is integrating this technology into HVAC systems used for infrastructure cooling. For example, Magrini *et al.* reported 425 L/h of water could be generated by recovering the condensate of the HVAC system cooling a hotel in Iraq, which met nearly 25% of their annual water demand.[89]

Thermoelectric cooling (TEC) devices based on the Peltier effect are an attractive alternative to VCR because of the small size, lack of moving parts and refrigerants, silent operation, and portability of these cooling elements. However, the cooling capacity of TEC devices is substantially lower than VCR, and unlike VCR, increasing the incoming flow rate diminishes performance.[90] Researchers have focused on developing new thermoelectric materials and coatings, thermal management, and TEC design to increase the efficiency of TEC-based AWH systems. Water generation rates of TEC based AWH systems are typically on the order of 0.025 L/h in tropical environments while consuming 20–70 watts of power.[91,92] Therefore, TEC devices need to be stacked to collect an appreciable amount of water. Due to their limited water collection capacity, TEC technology might be better suited for small, lightweight devices that are used in emergency situations rather than a means to supplement daily water consumption.

3.4.3. Sorbent-based Approaches for AWH

In the active-cooling schemes, energy is wasted in cooling the incoming air. Water vapor concentration is an AWH approach that seeks to reduce operational cost and energy requirements by condensing water vapor by a sorption technique. In sorption-based AWH, a sorbent material is used to capture water vapor from the atmosphere. The sorbent material is then heated to release water vapor, which is condensed to liquid water at ambient temperature. First-generation sorbent materials used for this technology include desiccants such as silica gel, zeolites, and hygroscopic salts. The critical properties for sorbent material are high water uptake capacity, rapid cycling between water vapor adsorption/desorption, and low desorption energy. ***The latter presents a major challenge as hygroscopic materials commonly used as desiccants inherently require high temperatures for water desorption, along with the diminishing performance of this technology at lower RHs.***

Two classes of materials that have garnered much attention as advanced sorbent materials are metal-organic frameworks (MOFs) and phase-change materials (PCMs) such as poly(N-isopropylacrylamide) (PNIPAAm). MOFs, which are constructed from inorganic clusters joined by organic linkers (**Figure 22**),[93] are attractive because their pore structure and chemistry are highly tunable. MOFs can adsorb water vapor through three mechanisms: *i*) chemisorption on open metal sites, *ii*) capillary condensation, and *iii*) water clusters formation leading to pore-filling.[94] Because the adsorption mechanisms are active in different RH regimes, MOFs can be used across an expanded operational range. Increasing the porosity and pore volume enhances the water uptake capacity of MOFs. Abtab et al. achieved a water uptake capacity of 1.95 g per g of sorbent at 70 % RH in their chromium-based MOF.[92] However, use of larger pore volumes necessitates increased energy consumption to desorb water and regenerate the material; relatively high regeneration temperatures have limited the broad use of MOF-based AWH. Recently, Hanikel et al. demonstrate that low regeneration temperatures (40–55 °C) can be obtained by manipulating the binding strength of the initial water molecules, which provide physisorption sites to bind subsequent water molecules.[95] By tuning this property, they were able to extend the high water uptake regime of this MOF system from 20–100 % RH, but at the cost of a lower water uptake capacity, ~0.4 g of H_2O per g of sorbent.

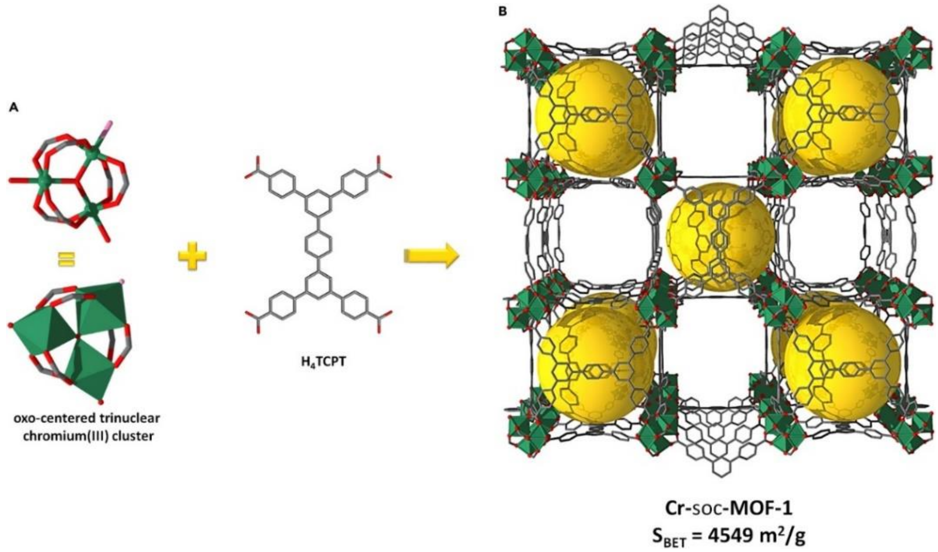


Figure 22. Crystal structure of a chromium-based MOF (Cr-soc-MOF-1). (A) The μ3-oxygen-centered trinuclear Cr(III) carboxylate clusters and organic linker (TCPT4−). (B) Molecular model showing the well-defined channels and cages found in Cr-soc-MOF-1. Color code: C, gray; O, red; Cl, pink; Cr, green; H, removed for clarity. Reproduced from Abtab et al., *Chem* 4 (2018) 94-105. Copyright 2018, Elsevier. DOI: 0.1016/j.chempr.2017.11.005.

Phase-change materials are popular in AWH systems because their transition temperatures, where their physical and/or chemically properties reversibly change, are generally much lower than the regeneration temperature of MOFs. As shown in **Figure 23**, phase-changing PNIPAAm/alginate hydrogels are hydrophilic and water adsorptive below the lower critical solution temperature (LCST) of ~32 °C. When heated above the LCST, PNIPAAm chains re-organize to present hydrophobic groups and shrink, causing adsorbed water to be expelled. The modest LCST temperature of these materials make them ideal for solar-driven AWH devices where solar irradiation triggers water expulsion from PCMs. While these devices have low power demands, their water production is, at most, a few L/kg of sorbent per day.[78]

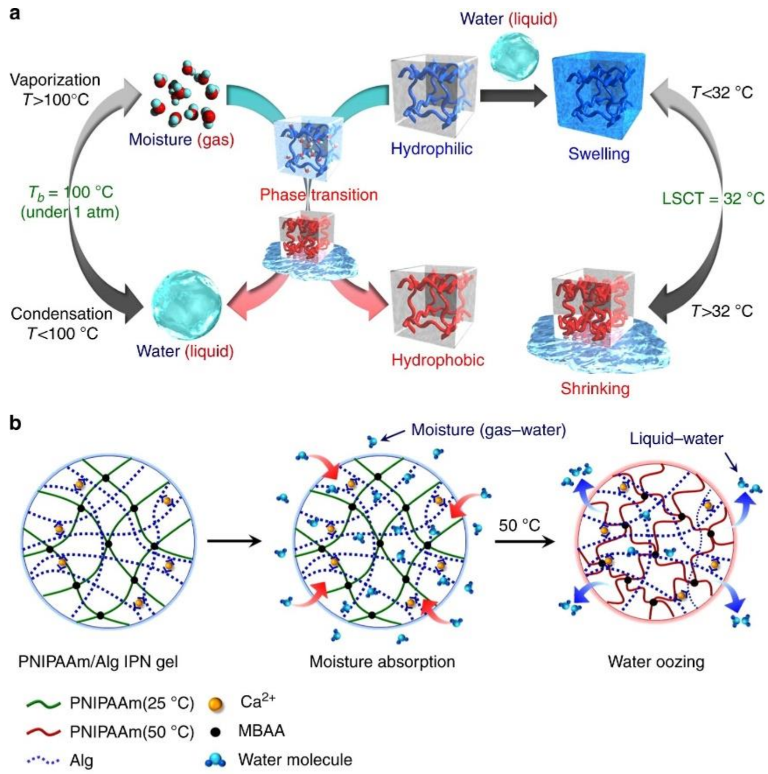


Figure 23. Conceptual illustrations of the water adsorption and water expulsion behavior of dried a PNIPAAm/alginate interpenetrating network gel. Reproduced from Matsumoto et al., *Nature Commun*. 9 (2018) 1–7. Copyright 2018, Springer Nature. DOI: 10.1038/s41467-018-04810-8.

In FY20, DARPA launched an Atmospheric Water Extraction program that continues through FY 24.[18] The aim of this program is to advance AWH technology, partially in arid environments, to reduce the burden of water resupply by fostering the development of technology that provides potable water without the need for an external liquid water source. The program is focused on two technical areas: (*i*) transformational sorbent materials development, and (*ii*) extractor modeling, engineering, and sorbent integration. Technology developed in the program addresses one of two program tracks: (*i*) expeditionary, a device for individual warfighters in the field, or (*ii*) stabilization, a device providing the daily drinking requirements for up to 150 people.[18] Table 3 lists the derived program metrics that developed devices should meet for ≥30 days of continuous operation.

Table 3. DARPA Atmospheric Water Extraction end-of-program objectives and metrics (BAA HR001120S0014 2019).

Program Track	Water Output	Size and Weight Requirements	Power Requirements
Expeditionary	≥5.5 L/day (4 °C, 50% RH) ≥5.5 L/day (27 °C, 10% RH) ≥7.5 L/day (43 °C, 60% RH)	Volume ≤1.5 liters (w/o reservoir); ≤2.5 kg (dry weight), including power source for 24- hour run-time	On-board power limited by size/weight requirements
Stabilization	≥1150 L/day (4 °C, 50% RH) ≥1150 L/day (27 °C, 10% RH) ≥1150 L/day (43 °C, 60% RH)	≤ 0.75 m^2, contained on a standard military palette; ≤138 kg (dry weight, military 4-man lift weight, 305 lbs.)	≤42 Wh/L (4 °C, 50 % RH) ≤42 Wh/L (27 °C, 10 % RH) ≤42 Wh/L (43 °C, 60 % RH)

3.5. Ancillary Considerations

The technological assessment above focuses primarily on desalination, or methods like AWH that circumvent the need for direct desalination. The ability to deliver water to potable standard will also require the removal/mitigation of various chemical contaminants that may be encountered, either of natural or human origin, as well as biological pathogens. Reverse-osmosis has some innate filtering capabilities for such purposes, but other approaches, such as the electrochemical desalination schemes, may require additional hardware for pre-filtering inlet water. The added complexity, cost, or logistics burden of these add-ons should be considered when ultimately selecting water-purification systems. A related concern is that of water-quality assessment. The following sub-section addresses that question in the context of specific needs for small-unit operations and ongoing programs that are seeking to address these anticipated requirements.

3.5.1. Assessing Water Quality

For all potable-water generation technologies, ensuring the water quality is suitable for human consumption is paramount. Technical Bulletin, Medical 577 (TB MED 577), "Sanitary Control and Surveillance of Field Water Supplies,"[5] is the tri-service guidance manual for short-term (≤ 30 days) and long-term (> 30 days) potability military field water standards (MFWS), and short-term military exposure guidelines (MEG) independent of consumption rates. MEG based on short-term (≤ 7 days) and long-term (≤ 1 year) water consumption are detailed in technical guide 230 (TG 230), "Environmental Health Risk Assessment and Chemical Exposure Guidelines for Deployed Military Personnel", which was developed by the U.S. Army Public Health Center.[96]

Before processing, guidelines stipulated that raw water sources be tested for the following parameters: pH, turbidity, total dissolved solids (TDS), color/odor, acute toxins (*i.e.*, arsenic and cyanide), and chemical warfare (CW) agents (hydrogen cyanide, lewisite, sulfur mustard, nerve agents). The recommended testing frequencies for water production, storage, and distribution systems are weekly/monthly for bacterial contamination (total coliforms and *E. coli*), TDS, free available chlorine (FAC), temperature, pH, color/odor, and turbidity. Concentrations of arsenic, cyanide, magnesium, chloride, and sulfate should be screened quarterly. Frequency of CW agent and radiological testing are determined by threat and mission-oriented protective posture (MOPP) level. Additionally, when field deployed, hourly inspection of water purification/production points are recommended to ensure FAC, turbidity, pH, and TDS of the drinking water remain at acceptable levels.

To address challenges associated with assessing water quality, the U.S. Army Development Command Soldier Center (DEVCOM SC) is supporting a water sensors program.[97,98] The aim of this program is to develop sensor platforms to enable warfighters to rapidly assess water quality in the field. DEVCOM SC conducted a front-end analysis ahead of the start of this program to survey the state-of-the-art water sensors technologies and identify critical gaps in capabilities. Commercial-off-the-shelf (COTS) kits used to assess these parameters are limited by the shelf life of their consumables and inadequate training of personnel; the full capacity of these kits is rarely used. To coordinate efforts to address these capability gaps, DEVCOM SC has established a Water Sensor Community of Practice (CoP) consisting of stakeholders and potential end users from each of the tri-services. The goal of this CoP are to provide situational awareness of government, industrial, and academic research and development efforts relating to emerging water sensor technologies, define the desired performance metrics for warfighter systems, and support transition of technologies to the field.[97,98]

4. SUMMARY & RECOMMENDATIONS

4.1. Summary of Technology Assessment

The success of expeditionary missions will require decentralized potable-water logistics, with greater focus on generation/purification technologies that do not require local freshwater sources. Given the prevalence of seawater and brackish inland water in many anticipated areas for expeditionary missions, the ability to efficiently and quickly desalinate water sources is a critical attribute for any new potable-water technology considered for such DoD applications.

Reverse osmosis will continue to be the predominant water-purification technology for large-unit operations, and has recently been scaled down to a platoon-scale device, however, there remains a need for individual and squad-scale water production devices that do not require fresh or brackish water inputs. Because RO is reaching its scalability limit, the search for viable small-scale treatment devices should be expanded beyond scaled-down RO to consider emerging technologies (**Table 1**). Recent breakthroughs in alternative potable-water technologies may prove advantageous for smaller scales where portability and simplicity are key attributes.

Aside from RO, electrochemical desalination has long been explored for deionizing brackish water and seawater, but prior-generation approaches that relied on conventional CDI could not meet performance demands for wide-spread use, particularly with high-salinity water feed. Over the past decade, through materials development and device engineering, new electrochemical approaches that adapt Faradaic/intercalative electrodes have improved the electrochemical desalination capacity and specific energy to competitive performance levels, and therefore demand attention for prospective DoD uses. Cell designs that incorporate two Faradaic/intercalative electrodes (e.g., RCDI, DEDI) are the most promising for moving the efficacy of electrochemical desalination to the high end of the brackish salinity range, and perhaps beyond, in terms of energy efficiency and output rate. In 2022, next-generation electrochemically based water-treatment technologies were the subject of an ONR-sponsored basic research solicitation. Since 2022, several Navy-sponsored basic research programs have commenced dedicated to the development of high-capacity electrode materials, membrane-electrode assemblies, and advanced device designs (**Table 4**).

Metal–air desalination batteries represent a special case among electrochemical desalination devices in which the device offers the prospect of net-positive energy output during desalination, but at present require mechanically replaceable anodes. Among the various technologies assessed in this study, Faradaic/intercalative deionization and related desalination batteries should be considered for future water-purification needs, even as additional investment in research and development would be beneficial to move these promising technologies to higher TRL. In addition to improving desalination performance, these electrochemical approaches have the added benefits of design flexibility in terms of scaling the system toward personal and small-unit specifications, low-signature operation, energy efficiency, and compatibility with electrical output from present military power-source hardware.

Atmospheric water harvesting strategies bypass the need for direct desalination, instead drawing from local sources of water vapor. Although, at present, AWH has low water production rates and is highly energy intensive, the unique ability of this technology to function independent of a freshwater or saline water supply is a key advantage that makes AWH worthy of further attention. Recent studies suggest enhancements in the performance of AWH technologies can be achieved by further innovations in sorbent materials and chemical and/or physical modifications to collection surfaces. Because AWH is heavily dependent on the ambient temperature and humidity, the water production rates will always be dictated by the deployment location and its seasonal climate. Nevertheless, there is great value in the continued investment in AWH technologies as supplemental and emergency water supplies that can reduce the logistics burdens associated with currently used primary water supplies.

Table 4. Summary of recent Navy-sponsored basic research projects for electrochemical-based, small-scale water purification

Program (start)	Institution	Sponsor
Integrated electrode-membrane assemblies for energy efficient MCDI across the salinity spectrum (FY22)	Penn State University	Office of Naval Research, 6.2
Lightweight, Efficient, and Flexible Expeditionary Freshwater Production Enabled by Intercalative Faradaic Deionization with Patterned, Stacked Electrodes (FY22)	University of Illinois Urbana-Champaign	Office of Naval Research, 6.2
High-performance capacitive deionization based on novel polyelectrolyte-infused intercalation electrodes to achieve seawater-to-potable-water desalination (FY22)	Vanderbilt University	Office of Naval Research, 6.2
Evaluation of Intercalative Deionization for Brackish Desalination in Complex Waters (FY22)	George Washington University	Office of Naval Research, 6.2
Next-generation desalination/decontamination system for efficient production of potable water (FY22)	U.S. Naval Research Laboratory	Naval Research Laboratory Base Funds, 6.2
Electrochemical Desalination Testing and Water SME Activities at the NRL (FY23)	U.S. Naval Research Laboratory	Office of Naval Research, 6.2

Table 5. Summary of performance attributes of various water desalination/purification technologies.

Technology	PROs	CONs	Future Prospects for Small-Scale Devices
RO	• Best technique for high salinity (seawater) • Versatile: Purify fresh, brackish, or seawater • Mature technology	• Less efficient/cost effective at low salinity • Large footprint • Large energy utilization • High consumables burden • Pumping limits scalability	RO is a mature desalination technology. Required high pumping pressures limit its scalability. Incremental improvements will come from better pre-filtration, advanced membrane designs, and more efficient pumping and energy-recovery devices.
FO	• No pumping needed, can be gravity fed • Reduced risk of membrane fouling relative to RO	• Slow • Requires consumables • Energy efficiency limited by draw solution recovery • Volume/mass of draw solution limits scalability	Utility of FO is limited by need for effective draw solutions that are easily recycled. Required volume and mass of draw solutions and inherently slow rate of FO make it a non-viable option for small-scale, expeditionary devices.
CDI/mCDI	• Prospect for energy recovery on “discharge” • High cycling rates • Low pressure: low or no pumping cost	• Limited by capacity of carbon electrodes • Short cycle time before regeneration needed • Carbon materials prone to corrosion/degradation • Membrane fouling and maintenance is a concern	Improvements in CDI require the development of: a) protective coatings to prevent electrode corrosion and b) fouling resistant membranes. Inherent low desalination capacity with CDI/mCDI limits utility for small-scale devices or high-salinity feeds.
FDI/IDI (RCDI, DEDI)	• Higher-capacity (2–8 ×) active materials than CDI • More volume desalinated between regeneration steps • Faradaic/Intercalation materials relatively inexpensive • Ion-selective electrode materials • Low pressure: low or no pumping cost • Much design flexibility for cell configurations	• Better suited for moderate salinity (brackish) versus seawater • Long-term stability and cyclability of electrode materials needs to be demonstrated in some cases • Cation/anion-capture mechanisms are relatively slow with many Faradaic/Intercalative materials	Highly active area of scientific development, also leveraging from breakthroughs in battery and electrochemical capacitor technology. Further advancement to higher TRL will benefit from development of: a) additional high-capacity anion-intercalation materials; b) material and electrode designs that increase ion-uptake rates; (c) strategies to stabilize electrode materials for long-term operation; and d) fouling-resistant membranes. Well-suited to small-scale device designs and moderate-salinity (brackish) feeds.
Metal–air desalination batteries	• Net-positive energy output during desalination • Low pressure: low or no pumping cost • High capacity per desalination step	• Present designs are single use (primary battery); requires mechanical replacement of consumed anode • Rates are slow	Highly active area of scientific development, also leveraging from breakthroughs in metal–air battery technology. Performance would benefit from further improvement in performance of air-breathing cathodes. Electrically rechargeable variants would increase utility of desalination batteries. A promising option for small-unit operations for limited mission duration.
ED	• Continuous-mode operation • Mature technology	• Better suited for lower salinity • Energy inefficient	Challenging to overcome fundamental inefficiency of electrolysis driving mechanism at high salinity. Technology has likely reached its peak.

Table 5 (cont.). Summary of performance attributes of various water desalination/purification technologies.

Technology	PROs	CONs	Future Prospects for Small-Scale Devices
Desalination fuel cells	• Continuous-mode operation • Provides power during desalination	• Expensive system • Requires logistics to transport/store hydrogen fuel	Interesting technology from fundamental perspective. Advantages of providing power for other uses during desalination (similar to desalination batteries). Logistics burden of required hydrogen fuel will limit expeditionary applications until hydrogen is more readily available.
ICP	• Indiscriminant for variety of constituents including salt, bacteria, viruses, and particulates • Requires less pretreatment • Low pressure: low or no pumping cost	• Slow • Requires a secondary, sequential desalination step to reduce salinity to potable levels • High specific energy requirement at high salinity	Microfluidics devices are generally difficult to scale up for higher throughput, although prototypes have been developed. Parallel device designs are needed to improve throughput, which will greatly increase device mass and footprint. Due to low throughput, less promising than several other listed approaches for “on-demand” applications.
Solar-thermal-evaporation/ SDIE	• No external power required • Few moving parts • Minimal pumping involved	• Intermittency issues of solar-driven technology • Slow • Large footprint • Thermal signature	Active area of research, with improvements being made with advanced membrane designs. Potentially promising technology for stationary uses, but low throughput and intermittency of solar input makes this method unsuitable for mobile small-unit missions.
AWH	• No liquid water source needed! • Works in wide range of climates	• Needs high-rate forced air (2000 SLM) • slow: L/day range • Inefficient	Performance enhancements are likely to come from further innovations in sorbent materials and chemical and/or physical modifications to collection surfaces. Not as suitable for “on-demand” water-generation needs due to slow production rate. Major advantage is that AWH does not require access to liquid water source. Potential to be operated “on the go”.

4.2. Programmatic Considerations

Through various program offices and laboratories supporting the U.S. Navy, Marine Corps, and Army, the DoD has a successful history developing, validating, and deploying potable-water technologies and logistics strategies to meet the needs of its warfighters. The continuing success of these efforts will require concerted and coordinated efforts as new potable-water challenges are encountered. The down-sizing of potable-water technologies is one such challenge that is not being addressed by other U.S. government agencies with activities in water technology.[1] Therefore, the

[1] The “Water Treatment Interagency Working Group” (“WATR”) includes many government agencies (*e.g.*, Bureau of Reclamations, Department of Energy, Environmental Protection Agency, as well as relevant DoD entities) that are involved in the broader water-treatment/purification. This group meet annually for high-level discussions of their respective efforts and requirements.

DoD should exert leadership in this critical technology area, as directed toward the specific needs of its missions. Creating an associated Integrated Product Team (IPT) that includes key DoD subject-matter-experts and stakeholders from across the services would be beneficial for coordinating development efforts and generating a new “roadmap” for this application area. Based on directions outlined in the new roadmap, the IPT may also oversee future funding activities that span from 6.1 “Basic Research” to 6.4 “Advanced Component Development and Prototypes” and include the participation of academic institutions, government laboratories, and industry (*e.g.*, through SBIRs). The IPT and associated Community of Interest (CoI) should hold annual meetings for discussions of the latest developments in potable-water technology and updates as related to DoD needs.

As new potable-water technologies are developed, early-stage validation testing with reasonably functioning prototypes will be necessary, understanding that multiple prototype generation are often required before an optimized design is identified. In addition to desalination performance and durability testing, energy efficiency will be a key metric for determining the applicability of a particular technology for DoD use. Therefore, benchmarks and associated test protocols for volumetric/gravimetric energy consumption (per unit potable water produced) should be clearly defined and communicated to those charged with maturing said technologies. At a higher level, the Concept of Operations (CONOPS) and Concept of Employment (COE) for the emerging technologies identified in the report should be defined in order to direct the associated testing and field experimentation that will be required for validation.

The continued development of associated technology, particularly for diagnostic testing of water quality in the field, will also be critical for ensuring that integrated water-purification systems operate at maximum effectiveness. Cataloging anticipated contaminants or threat agents in particular locales would also aid in the implementation of potable-water technology that may be optimally adapted to a local environment.

REFERENCES

1. “Water Planning Guide.” Force Development Directorate, United States Army Combined Arms Support Command, Fort Lee, VA (2008). Available at https://quartermaster.army.mil/pwd/publications/water/Water_Planning_Guide_rev_103008_dtd_Nov_08_(5-09).pdf.
2. “Petroleum and Water Logistics Operations.” Marine Corps Combat Development Command, Quantico, VA (2005). Available at https://apps.dtic.mil/sti/pdfs/AD1003699.pdf.
3. “Water Support Operations.” (October 2015) ATP 4-44/MCRP 3-17.7Q. Available at https://armypubs.army.mil/epubs/DR_pubs/DR_a/pdf/web/atp4_44.pdf.
4. “Water Support Operations.” (December 2022) Army Techniques Publication ATP4-44 Washington DC., Marine Corps Reference Publication MCRP 3-40D.14, Lejeune, NC. Available at: https://armypubs.army.mil/epubs/DR_pubs/DR_a/ARN37080-ATP_4-44-000-WEB-1.pdf/
5. “Sanitary Control and Surveillance of Field Water Supplies,” Departments of the Army, Navy, and Air Force, TB MED 577/NAVMED P-5010-10/AFMAN 48-138_IP, 1 May 2020.
6. J. Dusenbury. “Reducing the Forward Operating Base Water Logistics Burden.” Presented at the Environment, Energy Security and Sustainability (E2S2) Symposium and Exhibition, 6 May 2009. Available online: https://apps.dtic.mil/sti/pdfs/ADA634181.pdf.
7. M. Brosig, P. Frawley, M. Jahn. M. Marsicek, A. Paris, M. Rose, A. Shambaljamts, N. Thomas (U.S. Army War College). “Implications of Climate Change for the U.S. Army.” (2019). Available at https://climateandsecurity.files.wordpress.com/2019/07/implications-of-climate-change-for-us-army_army-war-college_2019.pdf.
8. A. Corbett. “Expeditionary Advanced Base Operations (EABO) Handbook” (1 June 2018). Available at https://mca-marines.org/wp-content/uploads/Expeditionary-Advanced-Base-Operations-EABO-handbook-1.1.pdf.
9. P. S. Panicacci. “How to Do Logistics in EABO.” *Marine Corps Gazette* (December 2020) WE13–WE18. Available at https://mca-marines.org/wp-content/uploads/How-to-Do-Logistics-In-EABO.pdf.
10. J. J. Urban. “Emerging Scientific and Engineering Opportunities within the Water-Energy Nexus.” *Joule* 1 (2017) 665–688.
11. P. S. Goh, T. Matsuura, A. F. Ismail, and B. C. Ng. “The Water–Energy Nexus: Solutions towards Energy-Efficient Desalination.” *Energy Technol.* 5 (2017) 1136–1155.
12. F.O. Balling. “Army Portable Water Treatment Units.” 3 June 2009. Available at https://dokumen.tips/documents/army-portable-water-treatment-units-unclassifiedfouo-army-portable-water-treatment.html?page=1
13. B. Arias, J. Brito, B. Long, R. Nordahl, C. Reese, J. Saenz, and B. Varnava. “Feasibility Study of Portable Water Desalination Systems for Water Contingencies at Remote Navy Installations.” Technical Report TR-NAVFAC-EXC-EX-1901 (December 2018). Available at https://apps.dtic.mil/sti/citations/AD1064752.

14. R. Zhao, S. Porada, P. M. Biesheuvel and A. Van der Wal, Energy consumption in membrane capacitive deionization for different water recoveries and flow rates, and comparison with reverse osmosis. *Desalination* 330 (2013) 35–41.
15. M. Metzger, M.M. Besli, S. Kuppan, S. Hellstrom, S. Kim, E. Sebti, C.V. Subban, and J. Christensen. “Techno-economic Analysis of Capacitive and Intercalative Water Deionization.” *Energy Environ. Sci.* 13 (2020) 1544–1560.
16. “Individual Soldier/Small Unit Desalination Device.” U.S. Army, ARMY SBIR Solicitation A18-149, 24 August 2018.
17. “Man-portable, Low-power individual purifcation system,” DARPA SBIR Solicitation SB151-002, 2015.
18. “Atmospheric Water Extraction,” DARPA Broad Agency Announcement HR001120S0014, 2019.
19. “Low Power Water Purification System” USMC SBIR Solicitation N153-127, 27 August 2015.
20. “Parker Hannifin’s Platoon Water Purification System Awarded Contract with US Marine Corps,” Parker Hannifin Corporation, 15 June 2020, Press Release.
21. Parker Hannifin Corporation. (2023). Platoon Reverse Osmosis System H2O-PRO [Brochure].
22. Triton, Award Information for Phase II SBIR program to Triton, 2020.
23. Katadyn, https://www.katadyngroup.com/ch/en/8019948-katadyn-survivor-35~p6775.
24. “Man Portable Desalination System,” U.S. Army SBIR Solicitation A09-11, 2009.
25. Army, Army SBIR A10-146. 2010.
26. J. Yoon, H.J. Kwon, S.K. Kang, E. Brack, J. Han. “Portable Seawater Desalination System for Generating Drinkable Water in Remote Locations.” *Environ. Sci. Technol.* 56 (2022) 6733–6743.
27. A. Subramani and J.G. Jacangelo. “Emerging Desalination Technologies for Water Treatment: A Critical Review.” *Water Res.* 75 (2015) 164–187.
28. M. Elimelech and W.A. Phillip. “The Future of Seawater Desalination: Energy, Technology, and the Environment.” *Science* 333 (2011) 712–717.
29. M.H. Qin, A. Deshmukh, R. Epstein, S.K. Patel, O.M. Owoseni, W.S. Walker, and M. Elimelech. “Comparison of Energy Consumption in Desalination by Capacitive Deionization and Reverse Osmosis.” *Desalination* 455 (2019) 100–114.
30. J.R. McCutcheon, R.L. McGinnis, and M. Elimelech. “A Novel Ammonia-Carbon Dioxide Forward (Direct) Osmosis Desalination Process. *Desalination* 174 (2005), 1–11.
31. Z. Huang, L. Lu, Z. Cai, and Z.J. Ren. Individual and Competitive Removal of Heavy Metals using Capacitive Deionization. *J. Hazardous Mater.* 302 (2016) 323–331.
32. D.S. Babu and P.V. Nidheesh. A Review on Electrochemical Treatment of Arsenic from Aqueous Medium. *Chem. Eng. Comm*. 208 (2021) 389–410.

33. N. Y. Yip, D. Brogioli, H. V. M. Hamelers, and K. Nijmeijer. "Salinity Gradients for Sustainable Energy: Primer, Progress, and Prospects." *Environ. Sci. Tech.* 50 (2016) 12072–12094.
34. X. Zhou, W.-B. Zhang, X.-W. Han, S.-S. Chai, S.-B. Guo, X.-L. Zhang, L. Zhang, X. Bao, Y.-W. Guo, and X.-J. Ma. "Principles and Materials of Mixing Entropy Battery and Capacitor for Future Harvesting Salinity Gradient Energy." *ACS Appl. Energy Mater.* 5 (2022) 3979–4001.
35. S. Porada, R. Zhao, A. van der Wal, V. Presser, and P. M. Biesheuvel. "Review on the Science and Technology of Water Desalination by Capacitive Deionization." *Prog. Mater. Sci.* 58 (2013) 1388–1442.
36. F. A. AlMarzooqi, A. A. Al Ghaferi, I. Saadat, and N. Hilal. "Application of Capacitive Deionization in Water Desalination: A Review." *Desalination* 342 (2014) 3–15.
37. Y. Oren. Capacitive Deionization (CDI) for Desalination and Water Treatment–Past, Present, and Future (a Review). *Desalination* 228 (2008) 10–29.
38. V. Pothanamkandathil and C. A. Gorski. "Comparing Energy Demands and Longevities of Membrane-based Capacitive Deionization." *Environ. Sci Water Res. Technol.* Advance Article (May 2022) DOI: 10.1039.D2EW00188H.
39. J. C. Farmer, D. V. Fix, G. V. Mack, R. W. Pekala, and J. F. Poco. "Capacitive Deionization of NaCl and $NaNO_3$ Solutions with Carbon Aerogel Electrodes. *J. Electrochem. Soc.* 143 (1996) 159–169.
40. J. C. Farmer, G. V. Mack, and D. V. Fix. "The Use of Carbon Aerogel Electrodes for Deionizing Water and Treating Aqueous Process Wastes." Presented at the *Fourth International Congress on Environmentally Conscious Design and Manufacturing* (Cleveland, OH; July 1996). Available at https://apps.dtic.mil/sti/pdfs/ADA349202.pdf.
41. P. S. Goh, A. F. Ismail, and B. C. Ng. "Carbon Nanotubes for Desalination: Performance Evaluation and Current Hurdles." *Desalination* 308 (2013) 2–14.
42. L. Chang, Y. Fei, and Y. H. Hu. "Structurally and Chemically Engineered Graphene for Capacitive Deionization." *J. Mater. Chem. A* 9 (2021) 1429–1455.
43. M. Qin, A. Deshmukh, R. Epstein, S. K Patel, O. M. Owoseni, W. S. Walker, M. Elimiech. "Comparison of Energy Consumption of Desalination by Capacitive Deionization and Reverse Osmosis." *Desalination* 455 (2019) 100–114.
44. M. E. Suss, S. Porada, X. Sun, P. M. Biesheuvel, J. Yoon, and V. Presser. "Water Desalination via Capacitive Deionization: What is it and What can We Expect from It." *Energy Environ. Sci.* 8 (2015) 2296–2319.
45. M. E. Suss and V. Presser. "Water Desalination with Energy Storage Electrode Materials." *Joule* 2 (2018) 10–15.
46. B. Han, G. Cheng, Y. Wang, and X. Wang. "Structure and Functionality Design of Novel Carbon and Faradaic Electrode Materials for High-performance Capacitive Deionization." *Chem. Eng. J.* 360 (2019) 364–384.

47. F. Yu, L. Wang, Y. Wang, X. Shen, Y. Cheng, and J. Ma. "Faradaic Reactions in Capacitive Deionization for Desalination and Ion Separation*." J. Mater. Chem. A* 7 (2019) 15999–16027.

48. Q. Li, Y. Zheng, D. Ziao, T. Or, R. Gao, Z. Li, M. Feng, L. Shui, G. Zhou, X. Wang, and Z. Chen. "Faradaic Electrodes Open a New Era for Capacitive Deionization." *Adv. Sci.* 7 (2020) 2002213.

49. Y. Liu, K. Wang, X. Xu, K. Eid, A.M. Abdullah, L. Pan, and Y. Yamauchi. "Recent Advances in Faradic Electrochemical Deionization: System Architectures versus Electrode Materials." *ACS Nano* 15 (2021) 13924–13942.

50. P. Srimuk, X. Su, J. Yoon, D. Aurbach, and V. Presser. "Charge-transfer Materials for Electrochemical Water Desalination, Ion Separation and the Recovery of Elements." *Nature Rev. Mater.* 5 (2020) 517–538.

51. Y.M. Cai, Y. Wang, X.Y. Han, L.W. Zhang, S.C. Xu, and J.X. Wang. "Optimization on Electrode Assemblies based on Ion-doped Polypyrrole/Carbon Nanotube Composite in Capacitive Deionization Process." *J. Electroanal. Chem.* 768 (2016) 72–80.

52. F. He, P.M. Biesheuvel, M.Z. Bazant, and T.A. Hatton. "Theory of Water Treatment by Capacitive Deionization with Redox Active Porous Electrodes." *Water Res.* 132 (2018) 282–291.

53. J. Lee, S. Kim, C. Kim, and J. Yoon. "Hybrid Capacitive Deionization to Enhance the Desalination Performance of Capacitive Techniques." *Energy Environ. Sci.* 7 (2014) 3683–3689.

54. C. Xu, Z. Yang, X. Ahang, M. Xia, H. Yan, J. Li, H. Yu, L. Zhang, and J. Shu. "Prussian Blue Analogues in Aqueous Batteries and Desalination Batteries." *Nano-Micro Lett.* 13 (2021) 166.

55. Z.W. Guo, Y.Y. Ma, X.L. Dong, M.Y. Hou, Y.G. Wang, and Y.Y. Xia. "Integrating Desalination and Energy Storage using a Saltwater-based Hybrid Sodium-ion Supercapacitor." *ChemSusChem* 11 (2018) 1741–1745.

56. F. Dixit, K. Zimmerman, R. Dutta, N.J. Prakash, B. Barbeau, M. Mohsenis, and B. Kandasubramanian. "Application of MXenes for Water Treatment and Energy-Efficient Desalination: A Review." *J. Hazard. Mater. Part B* 5 (2022) 127050.

57. J. Ahn, J. Lee, S. Kim, C. Kim, J. Lee, P.M. Biesheuvel, J. Yoon. "High Performance Electrochemical Saline Water Desalination using Silver and Silver Chloride Electrodes." *Desalination* 476 (2020) 114216.

58. D.H. Nam and K.S. Choi. "Bismuth as a New Chloride-storage Electrode Enabling the Construction of a Practical High Capacity Desalination Battery." *J. Am. Chem. Soc.* 2017 (139) 11055–11063.

59. H. Kong, M. Yang, Y.C. Miao, and X.Y. Zhao. "Polypyrrole as a Novel Chloride-storage Electrode for Seawater Desalination." *Energy Tech.* 7 (2019) 1900835.

60. T. Kim and J. Yoon. "CDI Ragone Plot as a Functional Tool to Evaluate Performance in Capacitive Deionization." *RSC Adv.* 5 (2015) 1456–1461.

61. F. Chen, Y. Huang, L. Guo, M. Ding, and H.Y. Yang. “A Dual-ion Electrochemistry Deionization System based on AgCl–$Na_{0.44}MnO_2$ electrodes.” *Nanoscale* 9 (2017) 10101–10108.

62. V. Pothanamkandathil, J. Fortunato, and C. A. Gorski. “Electrochemical Desalination Using Intercalating Electrode Materials: A Comparison of Energy Demands.” *Env. Sci. Technol.* 54 (2020) 3653–3662.

63. D. Xu, W. Wang, M. Zhu, and C. Li. “Recent Advances in Desalination Battery: An Initial Review.”*ACS Appl. Mater. Interfaces* 12 (2020) 57671–57685.

64. M. Ghahari, S. Rashid-Nadimi, and H. Bemana. “Metal–air Desalination battery: Concurrent Energy Generation and Water Desalination.” *J. Power Sources* 412 (2019) 197–203.

65. Q. Liu, Z. Pan, E. Wang, L. An, and G. Sun. “Aqueous Metal–Air Batteries: Fundamentals and Applications.” *Energy Storage Mater.* 27 (2020) 478–505.

66. J. Dai, N. L. W. Pyae, F. Chen, M. Liang, S. Wang, K. Ramalingam, S. Zhai, Ch.-Y. Su, Y. Shi, S.C. Tan, L. Zhang, and Y. Chen. “Zinc–Air Battery-Based Desalination Device.” *ACS Appl. Mater. Interfaces* 12 (2020) 25728–25735.

67. “Self-Powered Desalination Battery for Individual Soldiers,” Lynntech Inc., U.S. Army Contract W911QY-19-P-0237, A183-149-0257. Available online https://www.sbir.gov/node/1866501

68. S. Al-Amshawee, M. Y. B. M. Yunus, A. A. M. Azoddein, D. G. Hassell, I. H. Dakhil, and H. A. Hasan. “Electrodialysis for Water and Wastewater: A Review.” *Chem. Eng. J.* 380 (2020) 122231.

69. A. Campione, L. Gurreri, M. Ciofalo, G. Micale, A. Tamburini, and A. Cipollina. “Electrodialysis for Water Desalination: A Critical Assessment of Recent Developments on Process Fundamentals, Modeling, and Applications.” *Desalination* 434 (2018) 121–160.

70. S. Burn, M. Hoang, D. Zarzo, F. Olewniak, E. Campos, B. Bolto, and O. Barron. “Desalination Techniques–A Review of the Opportunities for Desalination in Agriculture.” *Desalination* 364 (2015) 2–16.

71. S. .K. Patel, P. M. Biesheuvel, and M. Elimelech. “Energy Consumption of Brackish Water for Desalination: Identifying the Sweet Spots for Electrodialysis and Reverse Osmosis.” *ACS ES&T Eng*. 2 (2021) 851–864.

72. Y. Zhang, L. Wang, and V. Presser. “Electrocatalytic Fuel Cell Desalination for Continuous Energy and Freshwater Generation.” *Cell Rep. Phys. Sci.* 2 (2021) 100416.

73. S. J. Kim, S. H. Ko, K. H. Kang, and J. Han. Direct Seawater Desalination by Ion Concentration Polarization.” *Nature Nanotechnol*. 5 (2010) 297–301. Erratum: *Nature Nanotechnol* 8 (2013) 609.

74. F. E. Ahmed, R. Hashaikeh, and N. Hilal. “Solar-Powered Desalination–Technology, Energy, and Future Outlook.” *Desalination* 453 (2019) 54–76.

75. F. Banat, R. Jumah, and M .Garaibeh. “Exploitation of Solar Energy Collected by Solar Stills for Desalination by Membrane Distillation.” *Renew. Energy* 25 (2002) 293–305.

76. X. Liu, D. D. Mishra, X. Wang, H. Peng, and C. Hu. Towards Highly Efficient Solar-driven Interfacial Evaporation for Desalination. *J. Mater. Chem. A* 8 (2020) 17907–17937.
77. W. Guan, Y. Guo, and G. Yu. “Carbon Materials for Solar Evaporation and Desalination.” *Small* 17 (2021) 2007176.
78. F. Zhao, X. Zhou, Y. Liu, Y. Shi, Y. Dai, and G. Yu. “Super Moisture-Absorbent Gels For All-Weather Atmospheric Water Harvesting.” *Adv. Mater.* 31 (2019) 1806446.
79. T. Oki, S. Kanae. “Global Hydrological Cycles and World Water Resources.” *Science* 313 (2006) 1068.
80. O. Klemm, R. S. Schemenauer, A. Lummerich, P. Cerceda, V. Marzol, D. Corell, J. van Heerden, D. Reinhard, T. Gherezghiher, J. Olivier, P. Osses, J. Sarsour, E. Frost, M. J. Estrela, J. A. Valiente, and G. M. Fessehaye. “Fog as a Fresh-Water Resource: Overview and Perspectives.” *Ambio* 41 (2012) 221.
81. J. K. Park, and S. Kim. “Three-Dimensionally Structured Flexible Fog Harvesting Surfaces Inspired by Namib Desert Beetles.” *Micromachines* 10 (2019) 201.
82. Y. Zheng, H. Bai, Z. Huang, X. Tian, F.-Q. Nie, Y. Zhao, J. Zhai, and L. Jiang. “Directional Water Collection on Wetted Spider Silk.” *Nature* 463 (2010) 640.
83. H. Chen, T. Ran, K. Zhang, D. Chen, Y. Gan, Z. Wang, and L. Jiang. “Highly Efficient Multiscale Fog Collector Inspired by Sarracenia Trichome Hierarchical Structure.” *Global Challenges* 5 (2021) 2100087.
84. M. Damak and K. K. Varanasi. “Electrostatically Driven Fog Collection Using Space Charge Injection.” *Science Adv.* 4 (2018) eaao5323.
85. G. Raveesh, R. Goyal, and S. Tyagi. “Advances in Atmospheric Water Generation Technologies.” *Energy Convers. and Manag.* 239 (2021) 114226.
86. H. Kim, S. R. Rao, E. A. Kapustin, L. Zhao, S. Yang, O. M. Yaghi, and E. N. Wang. “Adsorption-Based Atmospheric Water Harvesting Device for Arid Climates.” *Nature Comm.* 9 (2018) 1.
87. J. Patel, K. Patel, A. Mudgal, H. Panchal, K. K. Sadasivuni. “Experimental Investigations of Atmospheric Water Extraction Device Under Different Climatic Conditions.” *Sustain. Energy Technol. and Assess.* 38 (2020) 100677.
88. R. Tu and Y. Hwang. “Reviews of Atmospheric Water Harvesting Technologies.” *Energy* 201 (2020) 117630.
89. A. Magrini, L. Cattani, M. Cartesegna, L. Magnani. “Water Production From Air Conditioning Systems: Some Evaluations About a Sustainable Use of Resources.” *Sustainability* 9 (2017) 1309.
90. A. H. Shourideh, W. B. Ajram, J. Al Lami, S. Haggag, and A. Mansouri. “A Comprehensive Study of an Atmospheric Water Generator Using Peltier Effect.” *Therm. Sci. Eng. Prog.* 6 (2018) 14.
91. W. He, P. Yu, Z. Hu, S. Lv, M. Qin, and C. Yu . “Experimental Study and Performance Analysis of a Portable Atmospheric Water Generator.” *Energies* 13 (2019) 73.
92. S. Liu, W. He, D. Hu, S. Lv, D. Chen, X. Wu, F. Xu, and S. Li. “Experimental Analysis of a Portable Atmospheric Water Generator by Thermoelectric Cooling Method.” *Energy Procedia* 142 (2017) 1609.

93. S. M. T. Abtab, D. Alezi, P. M. Bhatt, A. Shkurenko, Y. Belmabkhout, H. Aggarwal, L. J. Weseliński, N. Alsadun, U. Samin, M. N. Hedhili, and M. Eddaoudi, "Reticular Chemistry in Action: A Hydrolytically Stable MOF Capturing Twice its Weight in Adsorbed Water." *Chem*, *4* (2018) 94-105.
94. M. J. Kalmutzki, C. S. Diercks, and O. M. Yaghi. "Metal–Organic Frameworks for Water Harvesting from Air." *Adv. Mater.* 30 (2018) 1704304.
95. N. Hanikel, X. Pei, S. Chheda, H. Lyu, W. Jeong, J. Sauer, L. Gagliardi, and O. M. Yaghi. "Evolution of Water Structures in Metal–Organic Frameworks for Improved Atmospheric Water Harvesting." *Science*, *374* (2021) 454-459.
96. "Environmental Health Risk Assessment and Chemical Exposure Guidelines for Deployed Military Personnel." Technical Guide 230. U.S. Army Public Health Command (2013). Available at https://phc.amedd.army.mil/PHC%20Resource%20Library/TG230-DeploymentEHRA-and-MEGs-2013-Revision.pdf.
97. "Chemical Sensors for Toxic Industrial Chemicals/Toxic Industrial Materials (TICs/TIMs) Filtration Performance Monitoring." U.S. Army STTR Soliciation A20B-T025, 6 May 2020.
98. E. Brack. "NSF P248.04 Military Operations Water Sensors: Chemical and Microbiological." Presented at the American Chemical Society 2023 Fall Meeting, 16 August 2023.